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CIVIL EFFECTS STUDY

BIOLOGICAL TOLERANCE TO AIR BLAST AND RELATED BIOMEDICAL CRITERIA

Clayton S. White, I. Gerald Bowen, and Donald R. Richmond

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BIOLOGICAL TOLERANCE TO AIR BLAST AND RELATED BIOMEDICAL CRITERIA

By

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NOTICE

ABSTRACT

Experience with animals exposed in a variety of above and below ground structures during full-scale field operations at the Nevada Test Site in 1953, 1955 and 1957 were reviewed. The data were assembled and summarized to illustrate the nature of the blast-induced problems of significance in protective shelters, "open" as well as "closed." Potential hazards were related to the following: various patterns of variation in environmental pressure; translational events associated with transient, high-velocity winds, ground shock and gravity involving the impact of energized inanimate objects on the one hand the the consequences of whole-body displacement on the other; non-line-of-site thermal phenomena including hot objects and rapidly moving hot, dust-laden air and debris; and dust, in the respirable size range, sufficiently high in concentration even in "closed" shelters as to warrant design measures to minimize or eliminate the occurrence of small particulates whether arising from wall spalling or otherwise. Tentative biological criteria, conceived to help assess human hazards from blast-related phenomena, were presented. Relevant data from the literature and ongoing research in environmental medicine were set forth to aid the reader in appreciating how the criteria were formulated, what information was extrapolated from animal data, and wherein "best estimates" were employed. "State-of-the-art" concepts were noted to emphasize areas in which more thinking and research must continue if more refined, complete and adequate criteria are to be forthcoming for assessing man's response to blast-induced variation in his immediate environment.

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BIOLOGICAL TOLERANCE TO AIR BLAST AND RELATED BIOMEDICAL CRITERIA

I. INTRODUCTION

Since experience at Hiroshima and Nagasaki[1,2] and studies at the Nevada Test Site[3-6] have indicated that survival following nuclear explosions can be sharply enhanced by suitable exposure inside open and closed structures, it is appropriate that a symposium on protective construction include an examination of selected biological information to help improve, if possible, survivability when structures either are modified to function as shelters or are initially designed to do so. That the material presented should encompass biomedical air blast criteria stems at least in part from the fact that the combination of hazardous nuclear-produced variations in the environment can not only be markedly altered by the conditions of exposure, but favorably influenced to assure blast survival at ranges relatively close to ground zero, a fact that has been demonstrated for animals in field tests at free-field overpressures near 90 psi for open[4,7,8] and about 175 psi for closed[6,9] underground structures. Also, test data are available on a simple structure buried at a location subjected to approximately 245 psi[10] which indicate that survival from blast-related hazards could have been highly probable.

To the contrary, events inside some structures due, for example, to pressure reflections and to winds funneling through entryways and other openings can, for certain locations and designs, enhance hazardous conditions considerably. In fact, dangerous translational effects for large yields and for certain burst conditions and exposure geometries, may extend to ranges that are close to those for significant free-field thermal effects on a hazy day, and they can easily occur at ranges far exceeding those for thermal burns when the latter must be due to scattered thermal radiation or hot, dust-laden air or debris because the geometry of exposure precludes direct-line-of-site application of thermal energy.

For these and other reasons, this presentation will attempt to deal with three related areas in a reasonably systematic way as follows. First, the nature of the blast-related phenomena that may be significant to occupants of protective structures will be noted and categorized. Also, relevant information from field studies will be reviewed.

Second, criteria for estimating human hazards from such phenomena will be presented even though those available are tentative, incomplete and only a beginning made in their formulation.[2, 11-14]

Third, supporting material and references from the literature, including those from a long-term, continuing program sponsored by the Division of Biology and Medicine of the U. S. Atomic Energy Commission since 1951 and by the Defense Atomic Support Agency of the Department of Defense since 1959, will be summarized briefly. Such information will aid those who would better understand the tenuous nature of the criteria and better appreciate the intraspecies biological studies as well as the related biophysical and physical investigations that have not only improved understanding the effects of blast from conventional explosives, but extended the data to include nuclear blast as well.

II. THE NATURE OF BLAST-INDUCED HAZARDS IN PROTECTIVE STRUCTURES

Though the magnitude and, to a much lesser extent, the character of blast-induced hazards as they relate to protective structures are much influenced by whether or not the structure — or shelter — is <u>open</u> or <u>closed</u>, the biomedical problems involved in either case are complex, not satisfyingly understood quantitatively (though better appreciated qualitatively) and on the whole pose more fascinating questions than there are data to provide firm answers. In general, the potential hazards can be categorized into five groups as noted below.

A. <u>Pressure Variations (Primary Effects)</u>

Variations in environmental pressure, both above and below the pre-detonation ambient, except in perfectly functioning shelters designed to be air tight, are likely to occur under "blast loading" in all "open" structures as well as "closed" ones that grossly fail or

malfunction in some way. Whether or not the pressure variations are biologically significant depends, among other things, on the magnitude, character and duration of the several components of the pressure pulse at or near the location of a biological target, especially if rapid, shock-like pressure changes occur in the early components of the pressure pulse.

Except for the longer durations of the over and underpressures characterizing "large" nuclear yields, examples of the pressure variations occurring inside protective structures, along with their differences from the free-field overpressures, can be cited from reports of projects carried out at the Nevada Test Site. Such selected and other relevant data are set forth below.

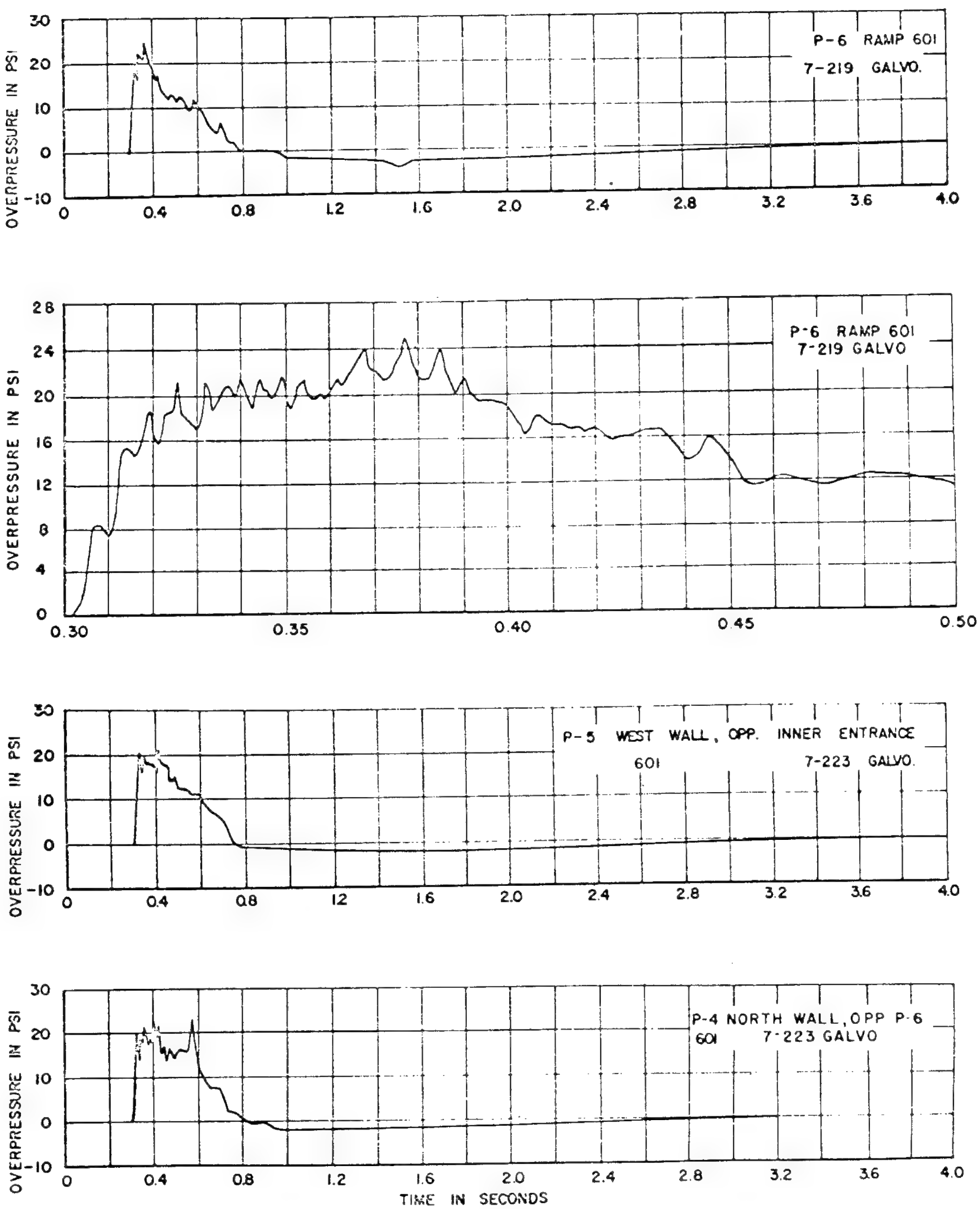
1. The 1953 "Open" Cylindrical Shelters

Following two nuclear detonations in 1953, pressure-time records were obtained inside two cylindrical underground structures, 50-ft long and 7 ft in diameter entered through walkdown ramps and doorless blast traps of two configurations.[15] Most of the Wiancko-gauge, pressure-time records available are shown in Figures 1 through 8.[15] Plane views of the structures are reproduced in Figures 9 and 10.[3]

The wave forms were atypical showing "early" and "late" components in the rise in overpressure, the latter probably due somewhat to the nonclassical, free-field pressure pulses, but mostly to reflections of pressure from the closed ends of the structure and from the equipment and test objects in the structures.

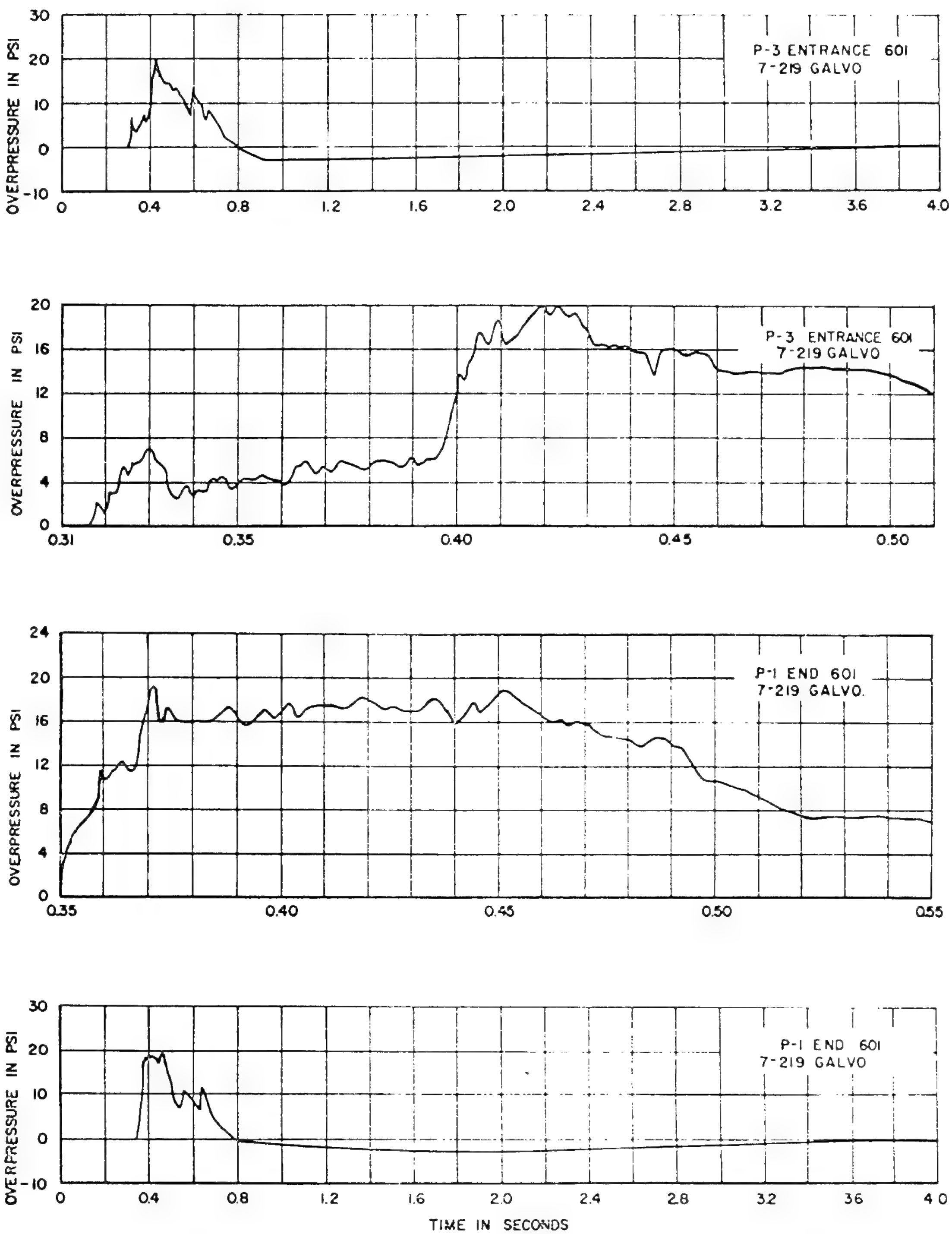
On one shot (Experiment I), the side-on, free-field overpressure outside the structures was approximately 13.5 psi.[15] The inside maximum pressures (including the ramps which faced ground zero) measured by flush-mounted wall gauges, ranged from 12.5 to 25 psi. The duration of the overpressures were from 430 to 570 msec and the average rates of pressure rise of either the first or second major component of the wave varied from almost instantaneous down to 440 psi per second.

On the second test (Experiment II), the ramps were at



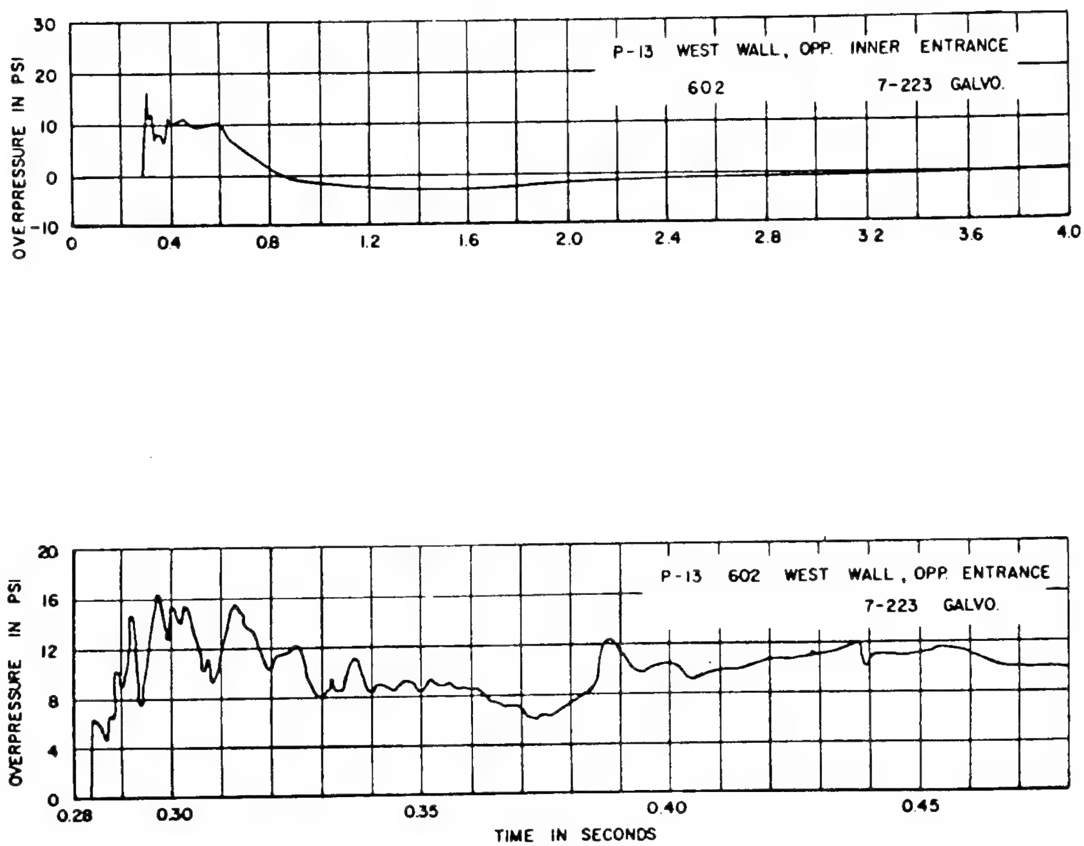
Pressure-time records inside entry ramp and blast trap of Structure 601 on Experiment I[15]

Figure 1



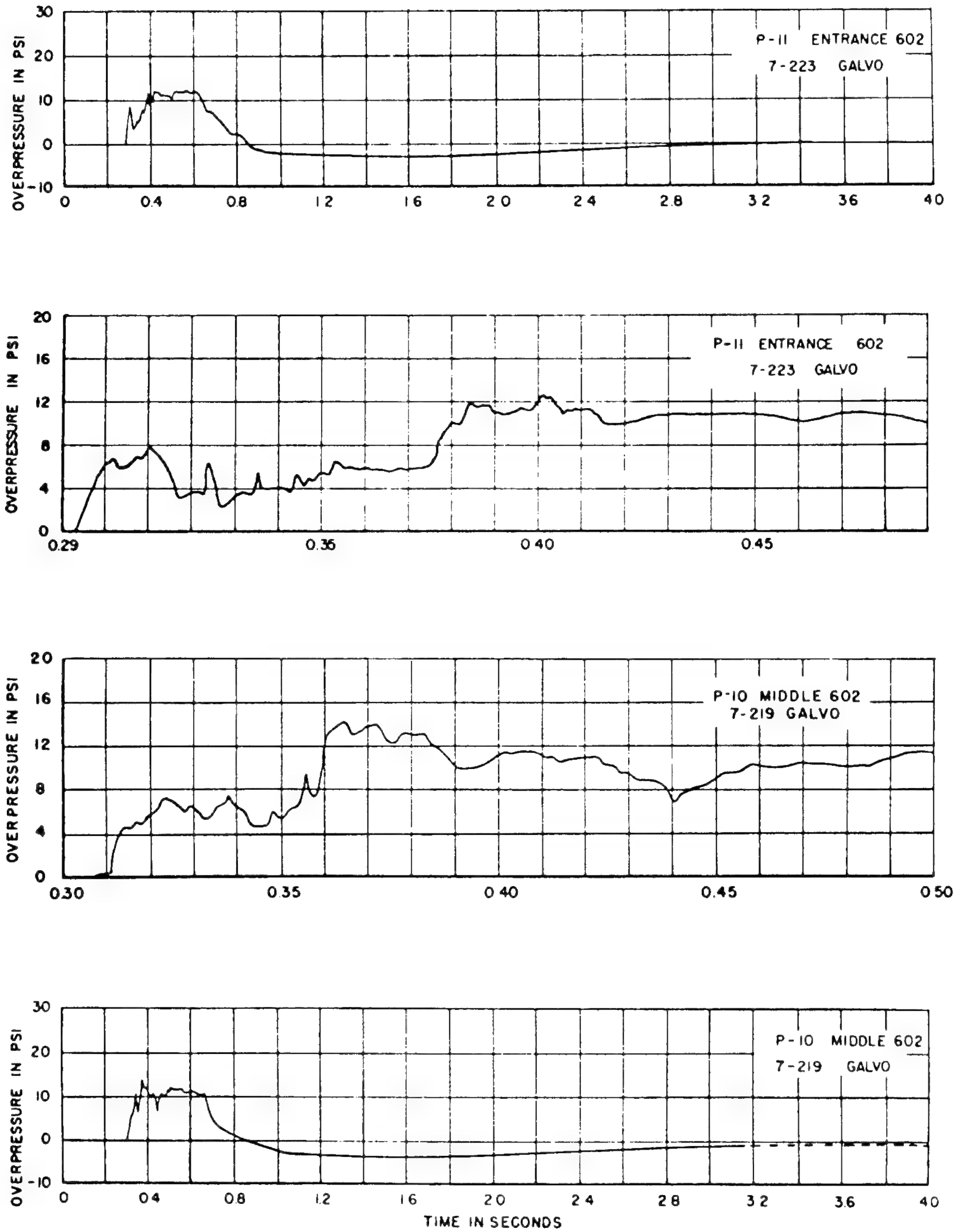
Pressure-time records inside main room of 601 Shelter on Experiment I[15]

Figure 2



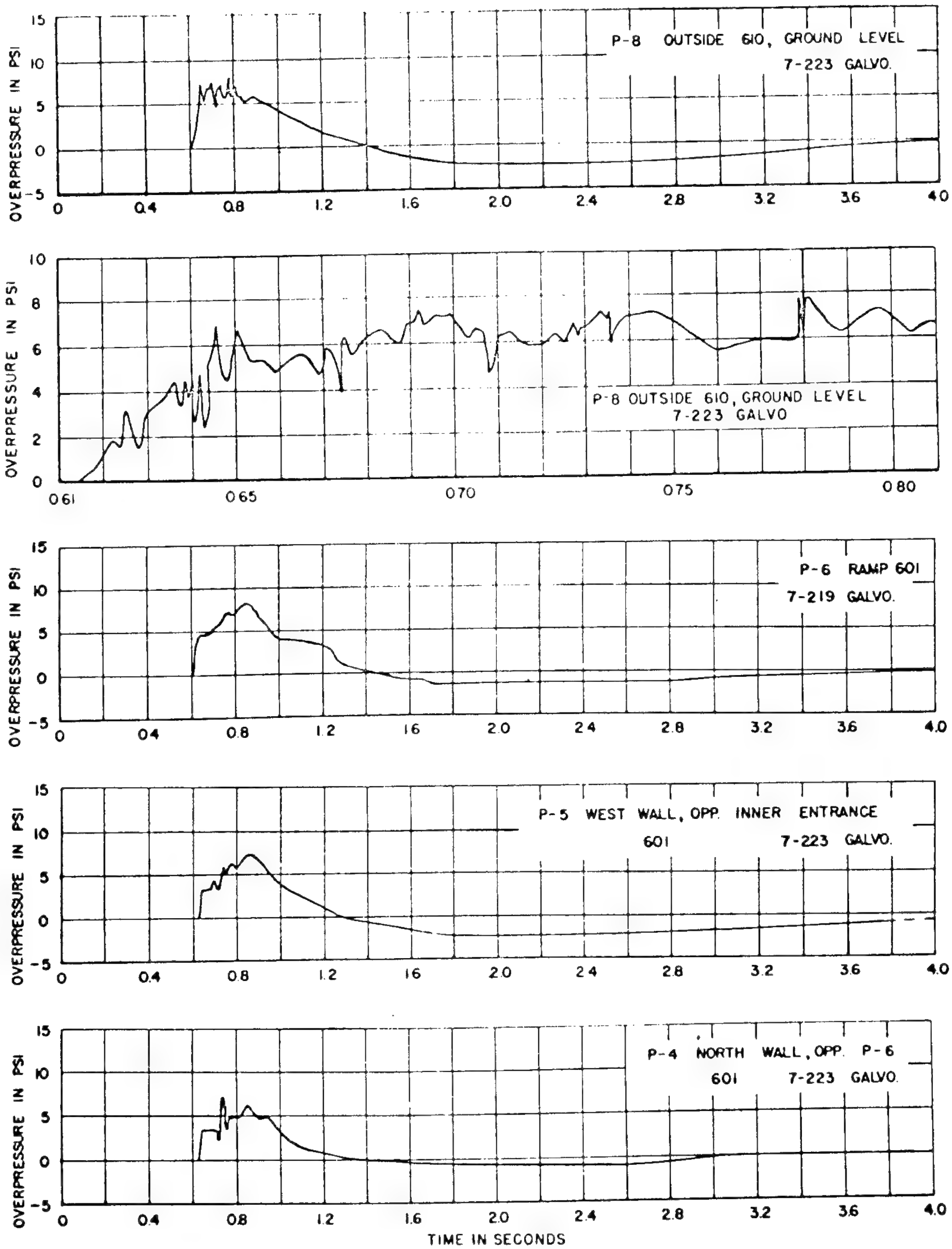
Pressure-time records inside blast trap of Structure 602 on Experiment I[15]

Figure 3



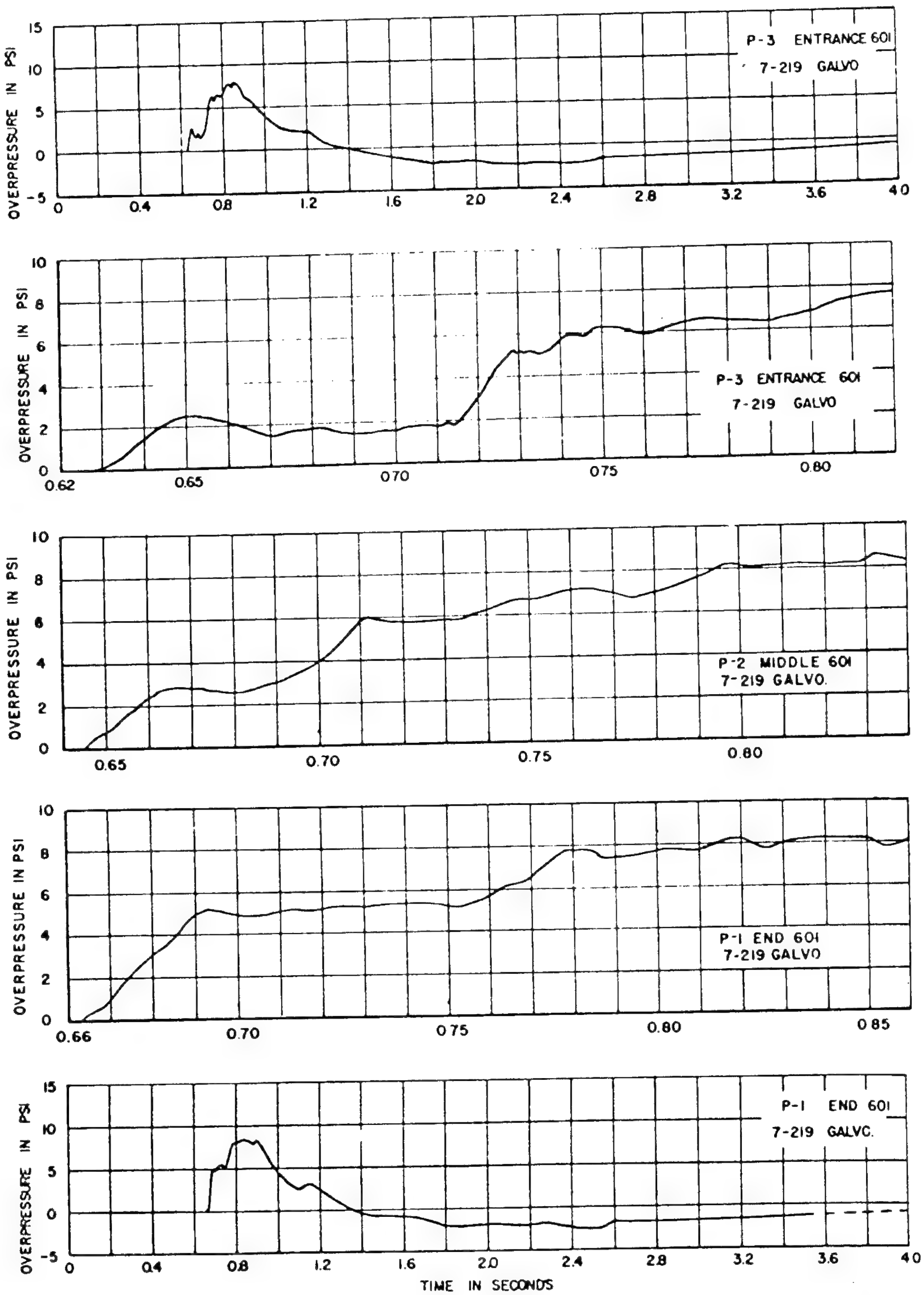
Pressure-time records inside main room of Shelter 602 on Experiment I [15]

Figure 4



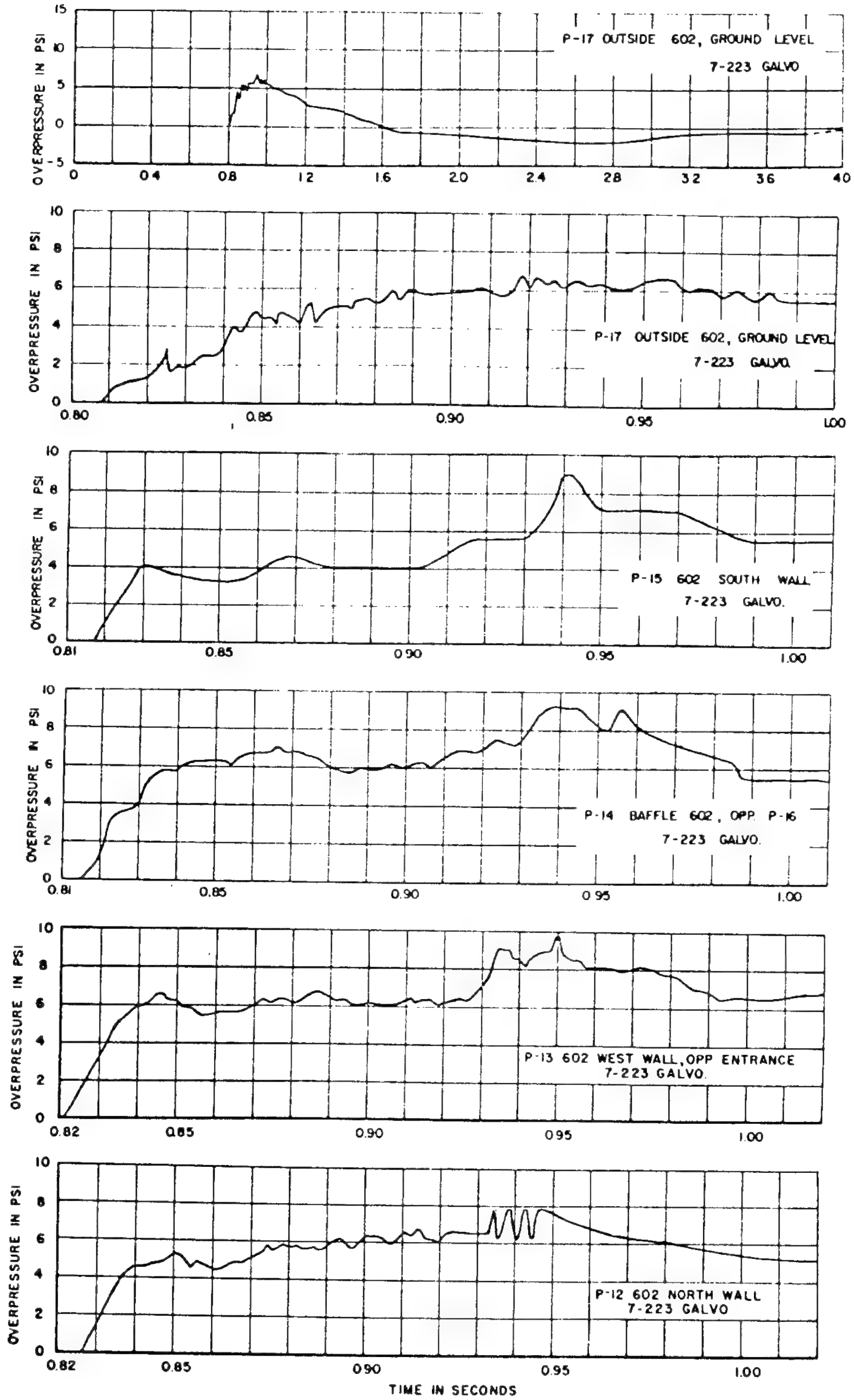
Pressure-time records outside and inside ramp and blast trap of Shelter 601 on Experiment II[15]

Figure 5



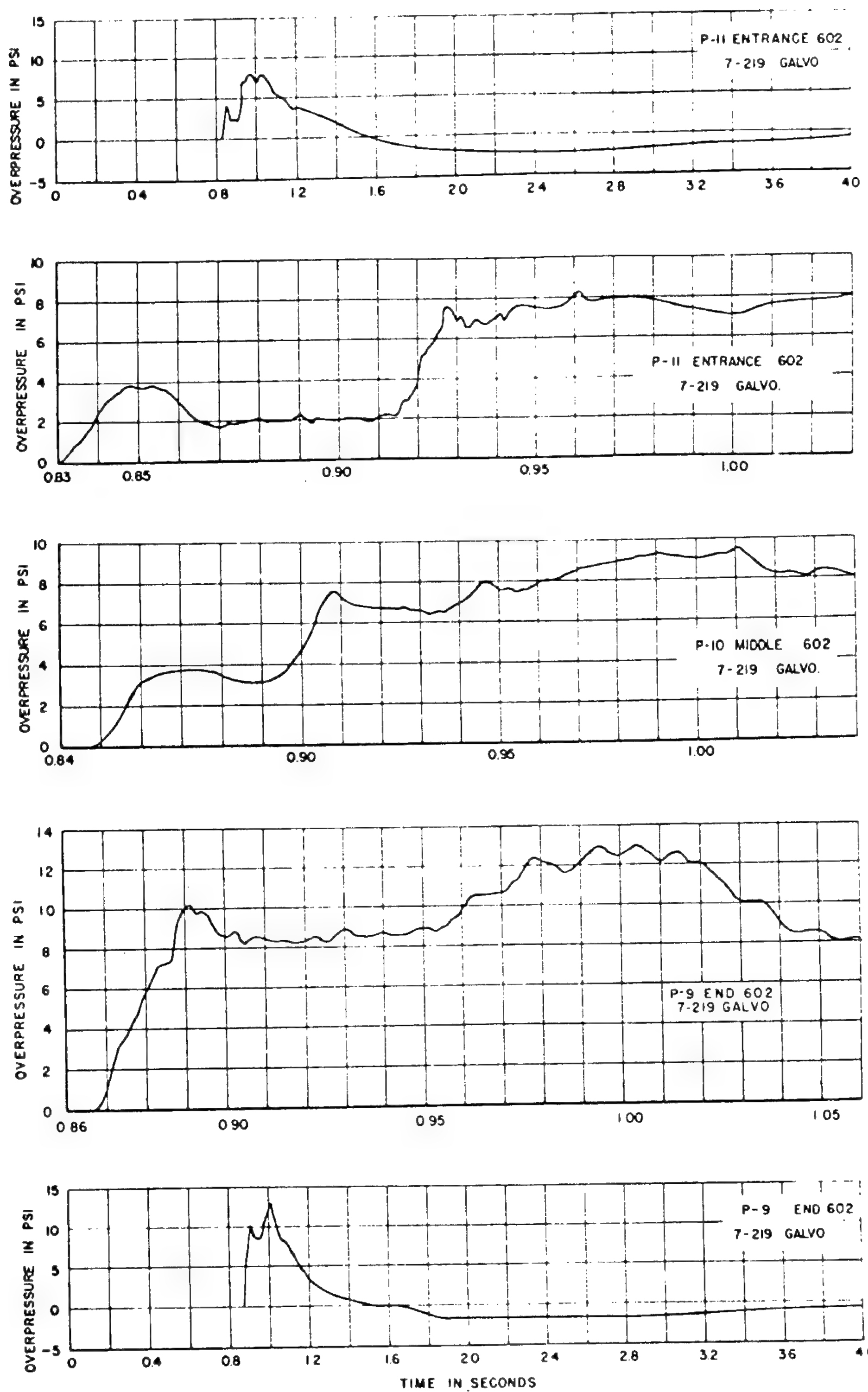
Pressure-time records inside main room of 601 Shelter on Experiment II [15]

Figure 6



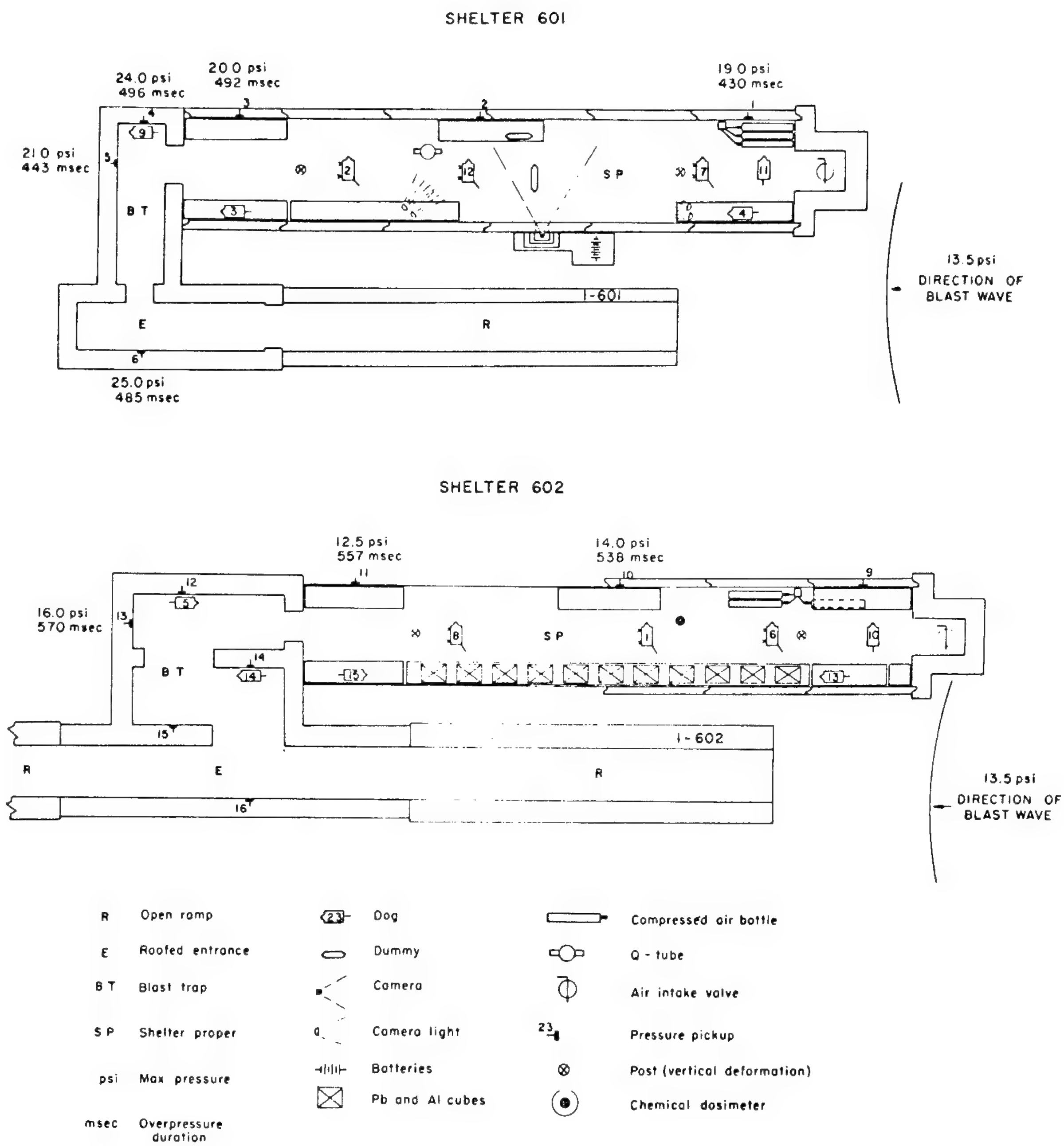
Pressure-time records outside and inside ramp and blast trap of Shelter 602 on Experiment II[15]

Figure 7



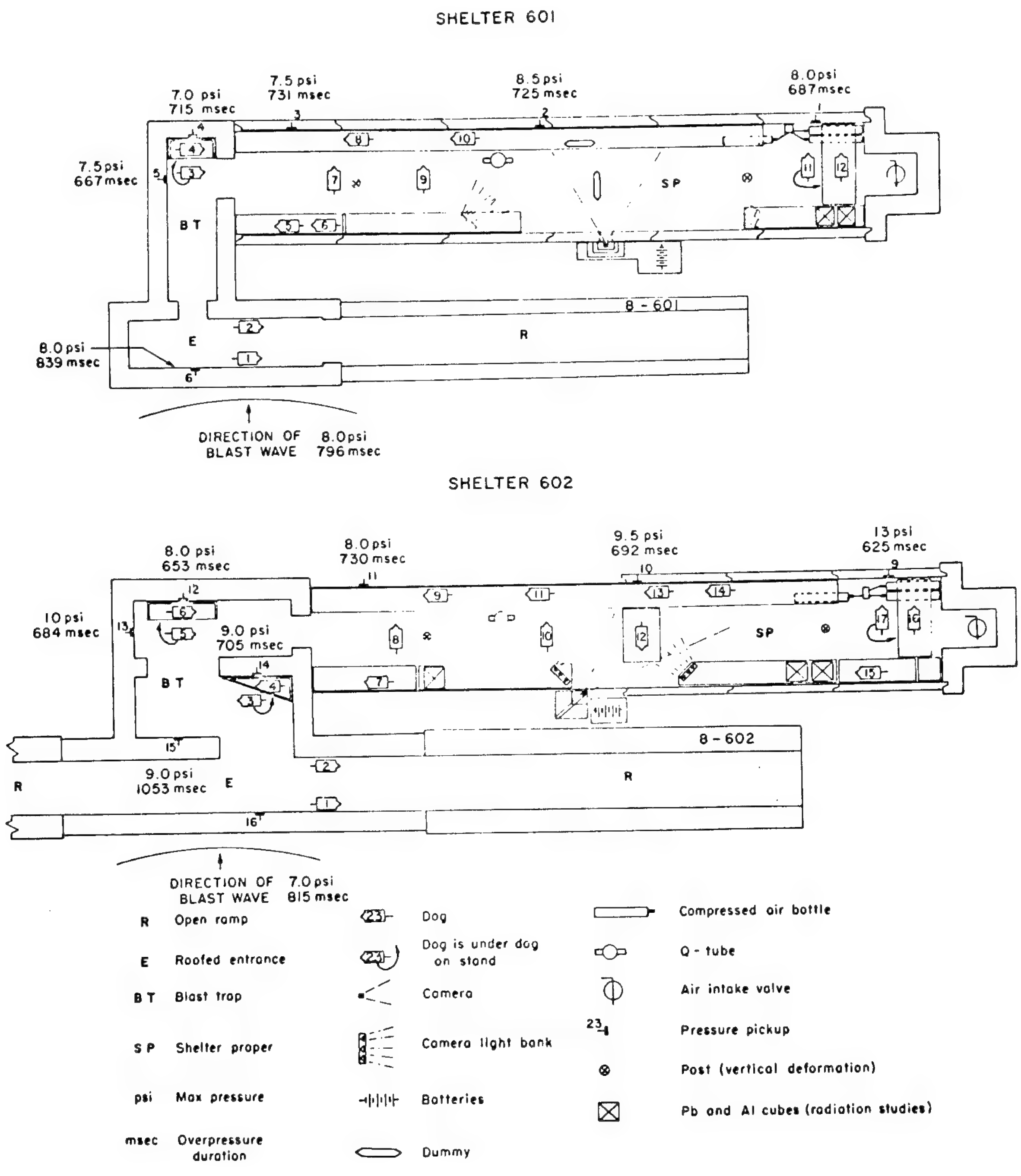
Pressure-time records inside main room of 602 Shelter on Experiment II[15]

Figure 8



Plan view of 601 and 602 Shelters and contents as used on Experiment I. Maximum recorded overpressures and their durations also shown.[3]

Figure 9



Plan view of 601 and 602 Shelters and contents as used on Experiment II. Maximum recorded overpressures and their durations also shown.[3]

Figure 10

right angles to the advancing blast wave. The maximum side-on, free-field overpressure was 7 to 8 psi. Inside the shelters, the maximum pressures ranged from 7 to 13 psi, the average rates of pressure increase for the two main components of the wave from 120 to 420 psi per second, and the pulse durations from 625 to 1053 msec.

The available pressure-time data for each shelter gauge are tabulated in Tables 1 and 2 which are arranged, as a glance at Figures 9 and 10 will show, in the order the gauges would be met if one walked down the ramp, entered the blast trap and proceeded on toward the end of the main rooms of the shelters.

A total of 44 dogs, trained to harness and carefully restrained to minimize or eliminate translational injuries, were studied — 15 on Experiment I and 29 on Experiment II.[3] The positive pathological findings are summarized in Tables 3 and 4. Except for tiny petechial lesions in the lungs of 5 of the 29 Experiment II animals plus one ruptured and 9 hyperaemic and occasionally hemorrhagic eardrums, all the blast lesions of interest occurred among the 15 dogs on Experiment I. Though no lethality due to overpressure was noted, the findings are significant and will now be noted more in detail.

General

Except for one distressed animal (602-15) that was chloroformed by an advance inspection party, all animals were recovered alive within 4.5 hours after the detonation. When first seen postshot, dog 602-14 was in shock, a condition due to an airway obstruction secondary to a large hematoma of the tongue. The animal recovered quickly when the tongue was pulled forward relieving the laryngeal obstruction. One-third of the animals (601-3 and 7; 602-14, 8 and 1) exhibited some degree of ataxia which persisted longer than 24 hours in three instances and until autopsy at 32 hours for case 601-7, 36 hours for 602-1 and 41 hours for 602-8. All animals were subdued and lethargic on recovery, but they ate and drank readily upon return to the base camp.

TABLE 1

ANALYSIS OF PRESSURE-TIME DATA – EXPERIMENT I[3]

SHELTER 601

Gauge No.	INITIAL RISE Pressure psig	INITIAL RISE Time msec	INITIAL RISE Av. Rate psig/msec	EARLY MAXIMUM RISE Pres. psig	EARLY MAXIMUM RISE Time msec	EARLY MAXIMUM RISE Av. Rate psig/msec	Second Rise psig	Max. Pres. psig	Duration Positive Phase msec
6	8.0	5	1.6	19	17	1.11	11.5	25.0	485
5	5.0	1	5.0	18	19	0.95	12.0	21.0	443
4	9.0	<1	Inst.	20	14	1.43	12.0	24.0	496
3	7.0	14	0.5	7	14	0.50	12.5	20.0	492
2	--	--	--	--	--	--	--	--	--
1	11.5	10	1.15	19	22	0.86	7.5	19.0	430
SHELTER 602									
16	--	--	--	--	--	--	--	--	--
15	--	--	--	--	--	--	--	--	--
14	--	--	--	--	--	--	--	--	--
13	6.5	<1	Inst.	16	13	1.23	11.0	16.0	570
12	--	--	--	--	--	--	--	--	--
11	6.5	8	0.81	8	17	0.42	6.0	12.5	557
10	7.0	16	0.44	7	16	0.44	7.5	14.0	538
9	--	--	--	--	--	--	--	--	--
SUMMARY: SHELTER 601 AND 602 – EXPERIMENT I									
RANGE:									
FROM	5.0	16	0.44	7	13	0.44	6.0	12.5	430
TO	9.0	Inst.	Inst.	20	22	1.23	12.5	25.0	570
OUTSIDE PRESSURE, BOTH SHELTERS (SANDIA BLAST LINE, SAME RANGE)								13.5	

TABLE 2

ANALYSIS OF PRESSURE-TIME DATA – EXPERIMENT II[3]

Gauge No.	INITIAL RISE Pressure psig	Time msec	Av. Rate psig/msec	EARLY MAXIMUM RISE Pres. psig	Time msec	Av. Rate psig/msec	Second Rise psig	Max. Pres. psig	Duration Positive Phase msec
SHELTER 601									
6	4.5	19	0.24	5.0	27	0.18	--	8.0	839
5	3.0	17	0.18	3.0	17	0.18	3.0	7.5	667
4	4.0	20	0.20	4.0	20	0.20	3.0	7.0	715
3	2.5	21	0.12	2.5	21	0.12	3.0	7.5	731
2	3.0	19	0.16	3.0	19	0.16	3.0	8.5	725
1	5.0	29	0.17	5.0	29	0.17	--	8.0	687
OUTSIDE PRESSURE									
8	3.0	10	0.30	7.0	30	0.23	--	8.0	796
SHELTER 602									
16	--	--	--	--	--	--	--	--	--
15	4.0	12	0.33	4.0	12	0.33	3.0	9.0	1053
14	6.0	21	0.28	6.0	21	0.28	2.0	9.0	705
13	6.5	24	0.27	6.5	24	0.27	3.0	10.0	684
12	4.5	13	0.35	5.0	23	0.22	--	8.0	653
11	4.0	18	0.22	4.0	18	0.22	5.5	8.0	730
10	4.0	22	0.18	4.0	22	0.18	4.5	9.5	692
9	10.0	24	0.42	10.0	24	0.42	--	13.0	625
OUTSIDE PRESSURE									
17	3.0	17	0.18	3.0	17	0.18	--	7.0	815
SUMMARY: SHELTER 601 AND 602 – EXPERIMENT II									
RANGE:									
FROM	2.5	10	0.12	2.5	12	0.12	2.0	7.0	625
TO	10.0	29	0.42	10.0	30	0.42	5.5	13.0	1053

TABLE 3

SUMMARY: PATHOLOGY NOTED – EXPERIMENT I*

SHELTER 601

Animal No.	Nearest Gauge No.	Max. Pres. psig	PATHOLOGIC LESIONS* Lung Hemorrhage	Middle Ear	Frontal Sinus	Heart	Omentum Mesentery	Spleen	Urinary Bladder
9	4	24	+ (BC)		+			+	
3	3	20	+				+		++
2	3	20	+ (BC)	+	+		+		+
12	2	--	+	+				+	
7	1	19	++				+		
4	1	19	++	++ (1R)	+		+		+
11	1	19	+++		+				++
SHELTER 602									
14	14	--	+++ (BC)				++	++	
5	12	--	++ (BC)	++ (1R)	+		+	+	++
	13	16							
15	11	12.5	+++ (BC)		+				
8	11	12.5	+	+					+
1	10	14.0	+	+	+	+			+
6	9	--	+++ (BC)	+	+				
13	9	--	+	+	+		+	+	+
10	9	--	+++ (BC)	+	+		+	+	++
TOTALS (FOR ALL 15 ANIMALS)			15	7 MINIMAL 2 DRUMS RUPTURED	10	1	8	6	9

*DEGREE OF DAMAGE: + = MINIMAL; ++ = MODERATE; +++ = MARKED.
(BC) = GROSS BLOOD CLOTS IN LUMEN OF BRONCHI; (1R) = RUPTURED EARDRUM.

NOTE: Data of Roberts et al.[3] rearranged.

TABLE 4

SUMMARY: PATHOLOGY NOTED – EXPERIMENT II[3]

SHELTER 601

ANIMAL NO.	NEAREST GAUGE NO.	MAX. PRES. PSIG	PATHOLOGY LESIONS* LUNG HEMORRHAGE	PATHOLOGY LESIONS* MIDDLE EAR
1	6	---		
2	6	---	P	
3	4	7.0	P	++(1R)
4	4	7.0		
5, 6, 7	3	7.5		
8	3	7.5	P	
9, 10	2	8.5		
11, 12	1	8.5		
		SHELTER 602		
1, 2	16	---		
3, 4	14	9.0		
5, 6	12	8.0		
7, 8	11	8.0		
9	11	8.0	P	
10	10	9.5	P	
11, 12 13, 14	10	9.5		
15, 16 17	9	13.0		
TOTALS (ALL 29 ANIMALS)			5	9(MINIMAL)** 1 DRUM RUPTURED

*DEGREE OF DAMAGE: P = TINY PETECHIA, R = RUPTURED EARDRUM.

**NINE ANIMALS, WHICH ARE NOT RECORDED, SHOWED HYPEREMIA OF THE EARDRUMS WITH AN OCCASIONAL HEMORRHAGE.

Lungs and Airways

Lung hemorrhages varied from irregularly disseminated spots of hemorrhage a few millimeters across to larger, confluent areas several centimeters in diameter. Often the hemorrhages followed a costo-phrenic alignment (the so-called rib markings).

Also, distinct and disturbing were large and small blood clots in the major bronchi of 7 of the exposed animals. In dog 602-14, an intraluminal blood clot formed a virtual cast of one entire lower lobe bronchus.

Heart

One animal (602-1) showed evidence of cardiac contusion; much of the left ventricular wall contained subendocardial hemorrhages.

Omentum and Mesentery

Scattered hemorrhages of the omentum and mesentery, seldom greater than 1 centimeter in size, were noted in 10 of the 15 animals.

Spleen

In 6 of 15 spleens examined, contusion and subcapsular hemorrhage (occasionally as large as 3 by 2.15 centimeters) were noted. The capsule was found torn in no instance, but was separated or sheared from the soft pulp, resulting in blood pooling beneath the capsule, which lifted the latter to form a bleb-like mound.

Urinary Bladder

Though no bladder perforations were noted, 9 of the dogs exhibited punctate hemorrhages and actual disruption of the bladder wall (mucosa, submucosa and part of the muscularis). Four of these (601-3, -11; 602-5, -10) had large mural tears resulting in irregular stellate ulcerations.

Ears

Small hemorrhagic areas were found in the middle-ear cavities of 9 animals and 2 of 30 eardrums were ruptured.

Comment

While it is probable that all of the animals (except possibly the one in serious condition from acute respiratory obstruction) would have survived, particularly if treated, the serious nature of the lung lesions were quite surprising at the time because the lowest overpressure produced by high explosives that was then known to be fatal for dogs was about 75 psi with a pulse duration of near 12 msec.

Also, without going into detail, there can be little doubt that morbidity, connected with lung hemorrhages (since pneumonitis would be a likely sequelae) and with the lesions of the mesentery, spleen and bladder, would have been high. Too, the occurrence of probable infection of the bladder, sinuses and ears, along with that of the lungs noted above, present the possibility of serious complications.

Four other comments seem pertinent here. First, a study of Tables 3 and 4 makes it apparent that there is no clear-cut correspondence between the degree of lung lesions and the magnitude of the local overpressure. Consequently, blast damage must be correlated with something other than, or in addition to, maximum overpressure.

Second, the tendency for the lung lesions to be highest near the closed ends of the shelters (a matter to be expected if the pressure pulse tended to "shock up" and if the average rate of pressure rise were a significant parameter in blast damage) is of interest.

Third, in general, significant pressure effects in the exposed dogs were associated with pressure-time conditions inside the shelters characterized by maximum overpressures between 12.5 and 24 psi, and average rates of pressure rise to or greater than 440 psi per second; to the contrary, few or minimal blast-pressure lesions

were seen when the P_{max} ranged from 7 to 13 psi and the average rates of pressure rise were less than or equal to 420 psi per second.

Fourth, the 1953 shelter experience pointed out the need to explore more fully the effectiveness of the duration of the over-pressure, known since the early part of the century[16] to be a significant blast parameter, but only studied quantitatively over the range from a little over one to almost 12 msec as can be noted in Table 5 which was prepared after the data of Desage.[17]

2. <u>The 1955 Shelter Studies</u>

In 1955 pressure-time data were recorded by Sandia Corporation in a variety of above and below ground structures exposed to nuclear-produced blast overpressures.[7,8] The free-field, side-on maximal pressures ranged from 5 to slightly over 90 psi for open and to 71.6 for closed structures. A variety of wave forms were documented as will be noted below.

<u>Houses (Range 4700 ft)</u>

Figure 11 is a reproduction of pressure-time traces obtained inside a lean-to (4.6 psi) and corner-room (3.7 psi) shelter in the basement of houses exposed to an incident maximum pressure of about 5 psi (lower record).[4,8] Also shown is the trace (top record) from a gauge located inside a reinforced concrete, bath-room shelter (1.3 psi) having a heavy, plywood shutter over the window and a plywood door to help minimize blast effects. The shutter and door served to delay the pressure rise inside the bath-room shelter, the peak reaching only about 25 per cent of the free-field maximal value. In contrast, the pressure inside the basement shelter was almost as high as outside the house. There was, however, an alteration (delay) in the rising phase of the pressure pulse.

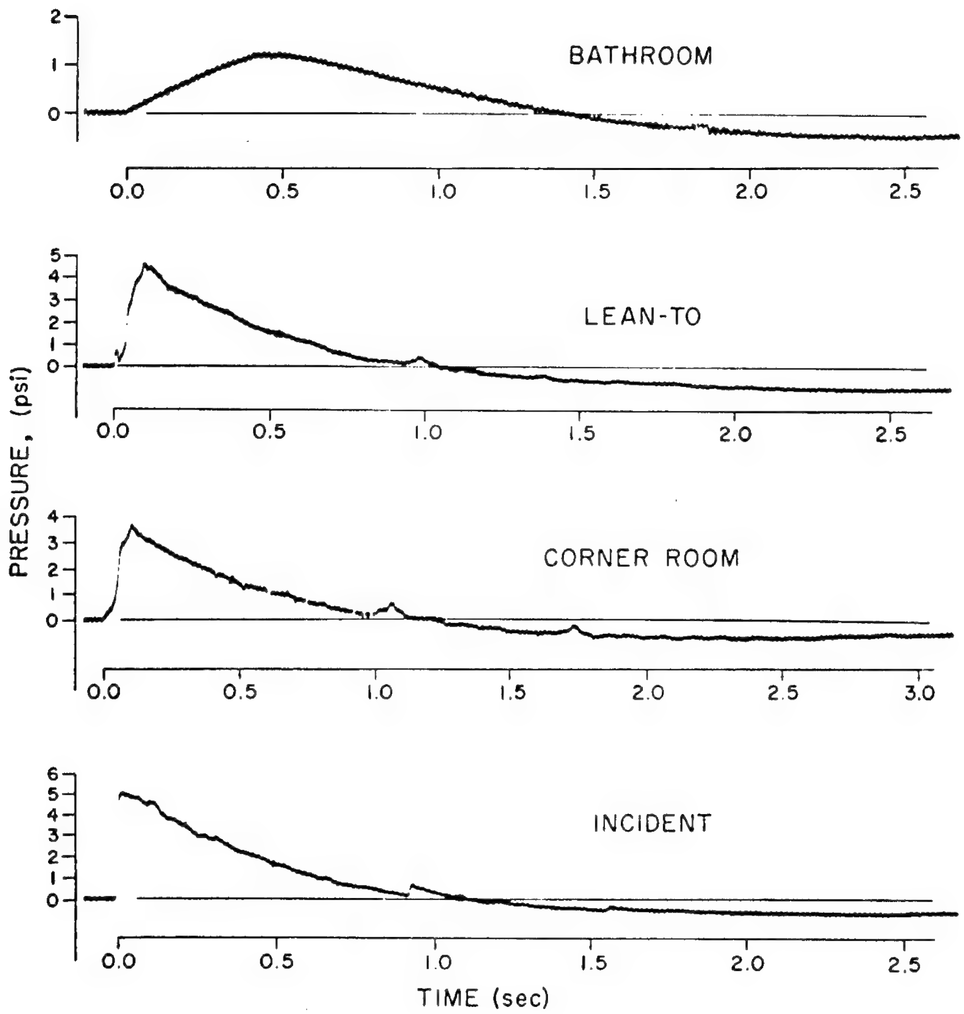
With the exception of one ruptured eardrum, the 6 dogs exposed in harness to avoid translational effects — two near each of the inside pressure gauges — exhibited no detectable pathology after the shot.[4]

TABLE 5

PRESSURE-DURATION RELATIONSHIP FOR NEAR 100 PER CENT MORTALITY IN DOGS EXPOSED TO "SHARP"-RISING, "SHORT"-DURATION HIGH EXPLOSIVE BLAST[17]

MAXIMUM STATIC OVERPRESSURE PSI	OVERPRESSURE DURATION MSEC
216	1.6
218	1.6
125	4.1
85	8.6
79	10.3
76	11.8

NOTE: ANIMALS, LYING ON THEIR SIDES WITH BACKS TO THE EXPLOSIVE, WERE EXPOSED ON LEVEL TERRAIN TO MOLDED CYLINDRICAL CHARGES DETONATED ON THE GROUND.



Pressure-time curves obtained near a house (incident) and inside shelters situated in the house (bathroom — ground floor; lean-to and corner room — basement)[4, 8]

Figure 11

Utility-Type Shelters

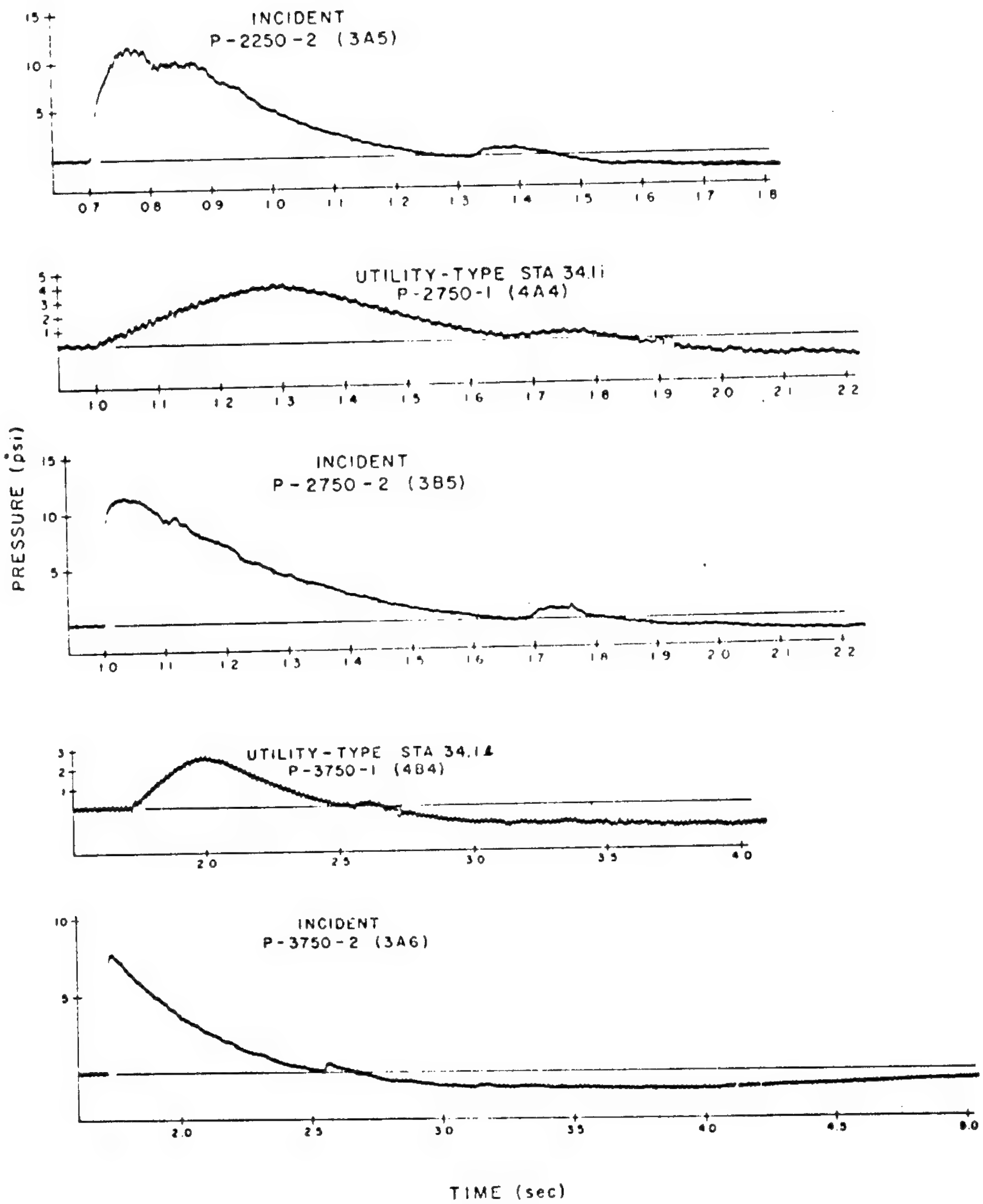
Three instrumented utility-type, reinforced concrete shelters, approximately 6-ft square and 7-ft high were exposed above ground at three different ranges. The roof of all structures was pierced by a 3-in diameter vent pipe, but the conventional and heavy, wooden doors of each were closed preshot. The close-in structure was "over-ended," but pressure-time records, shown in Figure 12 were obtained inside the other two. The figure also shows the free-field overpressure traces from ground baffle gauges placed near each of the three structures.

The three utility-type shelters, located at ranges of 3250, 2750 and 2250 ft received overpressures of 11.7, 11.6 and 7.8 psi, respectively. Maximum overpressures inside the middle and far-out shelters were 4.3 and 2.6 psi, respectively, both being more than 60 per cent below the peak outside pressure.

There were no injuries noted among four dogs, two each of which were recovered from the far-out shelters.[4] The two in the over-ended structure were injured, one fatally, but this was not attriuted to pressure variations. There were minor lung and sinus hemorrhages in the other animal. Unfortunately, the overpressure inside the structure was not recorded.

Basement Exit Shelters

On two series of experiments, 7 basement exit shelters were tested.[4,8] Each, entered by a steep stairway through a conventional door leading into an underground room 3 ft wide, 10 ft long and 5 ft high, were instrumented with 2 wall gauges, one near the door and one near the rear wall. The roof of all structures was pierced by a vent pipe. The ground-level portions of the entryway of 3 structures were protected by 4 heavy, wooden doors, ("closed"); one by 2 heavy, wooden doors (1/2 open) and the other 3 had no doors at the head of the stairs (open). Pressure-time data obtained inside the shelters and from nearby baffle gauges are tabulated in Table 6 and shown in Figures 13 and 14.



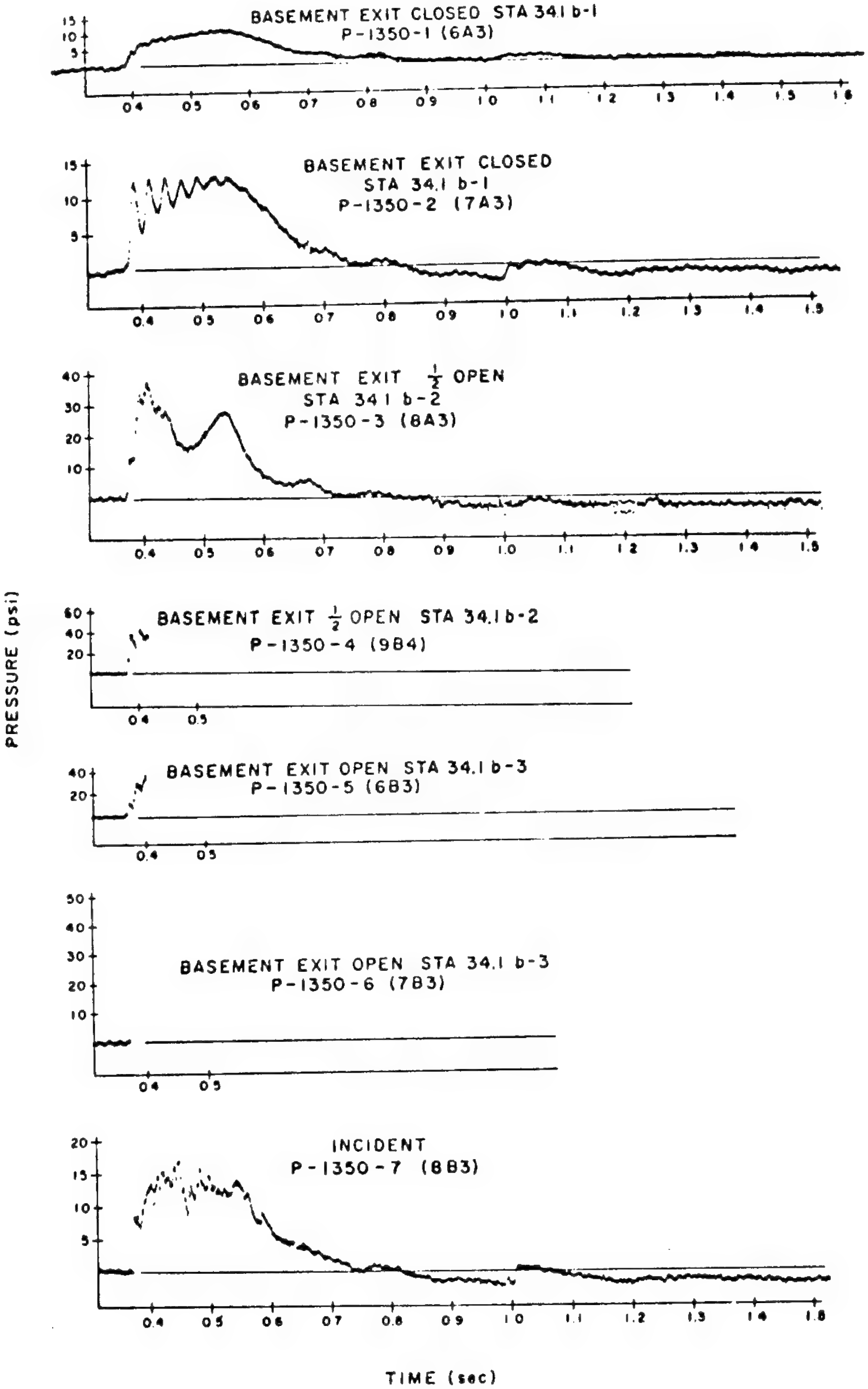
Pressure-time curves inside and outside utility-type shelters[4,8]

Figure 12

TABLE 6

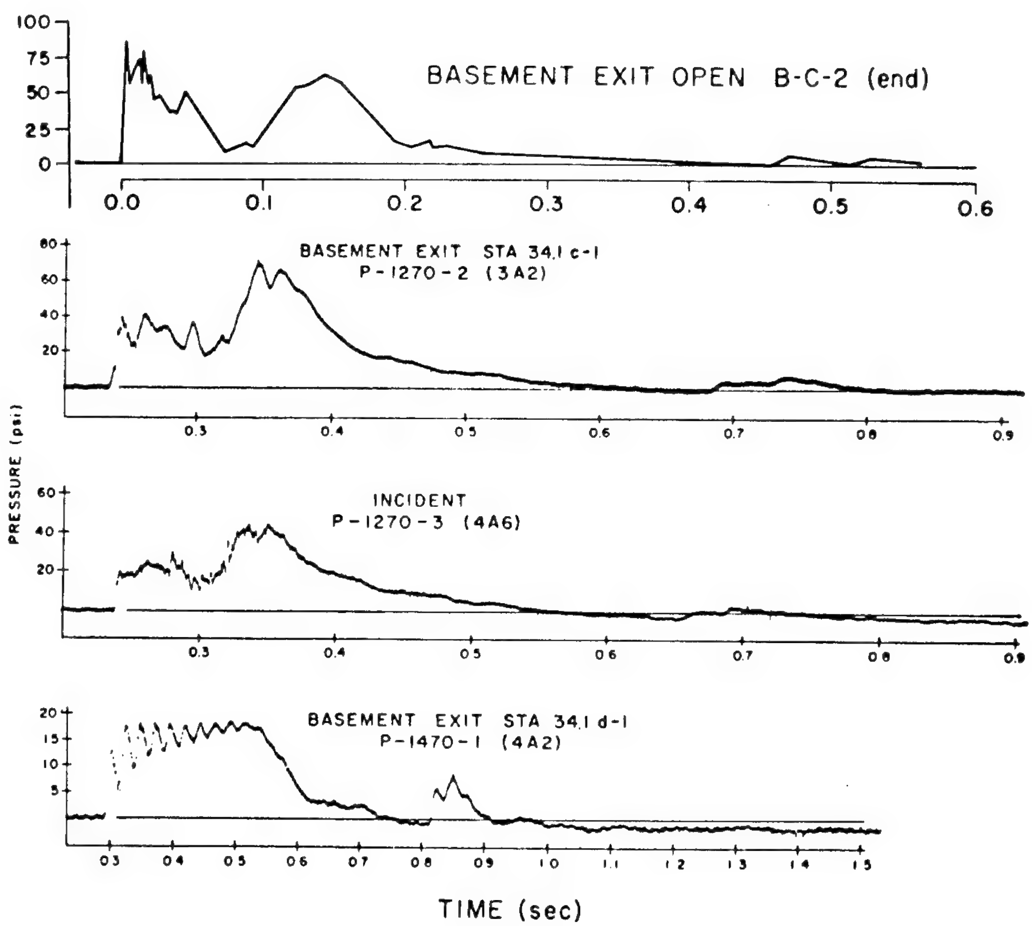
PRESSURE-TIME DATA INSIDE AND OUTSIDE THE BASEMENT EXIT SHELTERS[4, 8]

Series No.	Range in ft	Incident P_{max} psi	Shelter Entry-way	Internal P_{max} psi	Time to P_{max} msec	Duration Pos. Phase msec	Dog No.	Comment
I	1350	17.3	Closed	11.5	154	--	B-1-A	Doors failed
				13.5	57	736	B-1-B	
			1/2 Open	38.6	37	444	B-2-A	Doors blown
				47.0	22	--	B-2-B	away
			Open	38.6	36	--	B-3-A	
				43.1	5.5	--	B-3-B	
II	1470	--	Closed	18.5	57	685	B-D-1	Structural damage severe — doors blown away
							B-D-1-0	
			Open	53.0 (Est.)	5.0 (Est.)	(Gauges failed)	D-2	
							D-2-0	
II	1270	44.4	Closed	71.6	111	567	C-1	Severe structural damage — doors blown away, roof failed and
							C-1-0	
			Open	85.8	4	570	C-2	
							C-2-0	partly caved in



Pressure-time records inside and outside (incident) basement exit shelters (range 1350 ft)[4, 8]

Figure 13



Pressure-time records inside and outside (incident) basement exit shelters (ranges 1470 and 1270 ft)[4, 8]

Figure 14

It is interesting to note that, with the exception of one closed structure losing one of 4 doors, all other doors failed, both during the positive and the negative phases. However, some did function long enough to delay the "fill" of the structures as evidenced by the fact that the peak pressure inside one closed structure was 11-13 psi compared with an outside incident pressure of 17.3 psi.

In contrast, when there was early failure of doors (or as was the case for 1/2 or fully open structures — no doors), the maximum internal pressure was near or more than double that occurring outside the structure, i.e., see Table 6 showing a 43.1 psi internal maximum pressure associated with a 17.3 psi external pressure and a 85.8 psi internal with a 44.4 psi external pressure.

Also, it is of interest to note from Figures 13 and 14, the character of the wave forms recorded inside the structures. It is clear that oscillating pressures occurred, that the rising phase of the pulse often involved two or more steps and that the overall time to maximum pressure ranged from 4 to 154 msec. Thus, the average rate of pressure rise varied widely from about 75 psi per second to 21,375 psi per second.

Fourteen dogs were exposed, two inside each of the 7 basement exit shelters, with their sides parallel to the long wall of the structure closest to ground zero.[4] All animals, restrained in harness to prevent translation, were exposed to the left of the door at the bottom of the stairs; postshot pathologic findings are summarized in Table 7 from the top down in the order of increasing maximal pressure as they were measured inside the shelters. It is clear from the table that no, or only ear and sinus, pathology was associated with maximum exposure pressures of about 11 to 43 psi, times to P_{max} of 5.5 to 154 msec and average rates of pressure rise of 75 - 7836 psi per second.

In contrast, lesions to the thoracic and abdominal organs occurred at internal maximum pressure of near 39 - 86 psi, times to P_{max} of 4 - 111 msec and average rates of pressure rise of 645 to 21,375 psi per second. It may be significant, however, that no lung

TABLE 7*

RELATION BETWEEN ENVIRONMENTAL PRESSURE VARIATIONS INSIDE BASEMENT EXIT SHELTERS AND PATHOLOGIC FINDINGS IN EXPOSED DOGS. (ARRANGED IN ASCENDING ORDER OF MAXIMUM INTERNAL PRESSURE)

Range in ft	Shelter Entry-way	Internal P_{max} psi	Time to P_{max} msec	Av. Rate of Pres. Rise psi/sec.	Dog No.	Pathology Noted Postshot
1350	Closed	11.5	154	75	B-1-A	None
		13.5	57	236	B-1-B	None
1470	Closed	18.5	57	325	B-D-1	1 ruptured eardrum, focal hemorrhage middle ear, bilaterally
					B-D-1-0	1 ruptured eardrum, focal hemorrhage middle ear, unilaterally
1350	Open	38.6	36	1,072	B-3-A	2 of 2 eardrums ruptured
		43.1	5.5	7,836	B-3-B	None
SUMMARY:						
FROM		11.5	5.5	75		
TO		43.1	154	7,836		

*References 4 and 8.

(continued on next page)

TABLE 7 (Continued)

Range in ft	Shelter Entry-way	Internal P_{max} psi	Time to P_{max} msec	Av. Rate of Pres. Rise psi/sec	Dog No.	Pathology Noted Postshot
1350	1/2 Open	38.6	37	1,043	B-2-A	Splenic hemorrhage, 1 ruptured eardrum with focal hemorrhage middle ear
		47	22		B-2-B	Hemorrhage right frontal sinus, 1 ruptured eardrum
1470	Open	53 (Est.)	5 (Est.)	10,600 (Est.)	D-2	Minor lung hemorrhage; mucosal tear of urinary bladder; frontal sinus hemorrhage, bilaterally; one ruptured eardrum; bilateral focal hemorrhage middle ear
					D-2-0	Severe lung hemorrhage, bilateral eardrum rupture and focal hemorrhage middle ear
1270	Closed	71.6	111	645	C-1	Laceration urinary bladder, bilateral eardrum rupture
					C-1-0	One eardrum rupture; hemorrhage left frontal sinus
	Open	85.8	4	21,375	C-2	Moderate lung hemorrhage; subendocardial petechial; splenic hemorrhage; mucosal tear urinary bladder; frontal sinus hemorrhage, bilateral; eardrum rupture bilaterally
					C-2-0	Moderate lung hemorrhage; left extradural hemorrhage; subendocardial petechial; frontal sinus hemorrhage, bilateral; both eardrums ruptured
SUMMARY:						
FROM		38.6	4	645		
TO		85.5	111	21,375		

lesions were noted in dogs C-1 and C-1-0 for which the exposure conditions included a two-step rise in overpressure — see Figure 14, record 34.1 C-1 (second from top) — to a maximum of 71.6 psi in 111 msec at an average rate of 645 psi per second.

Group Shelters

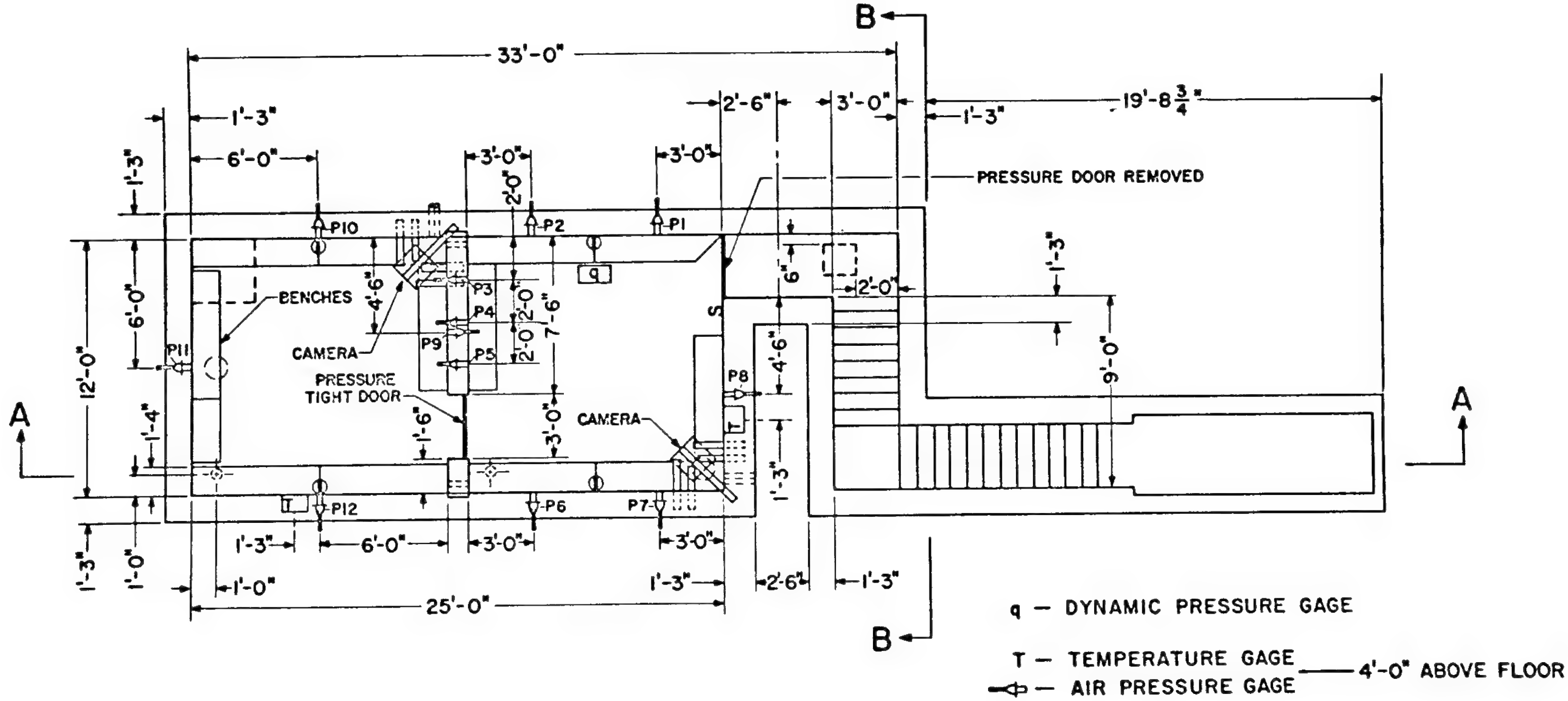
In 1955, two 12-x-25-ft underground group shelters, with 3-ft-square escape hatches and entered by L-shaped walkdown stairways and short halls, were each partitioned into two 12-ft square chambers, instrumented by Sandia Corporation[8] and utilized on two series of biological experiments.[4] The structures, one of which is shown in plan view in Figure 15, were used on both occasions with the partition doors closed, but with the escape hatches and main entryways fully open. Pressure-time curves recorded inside and outside the structures are shown in Figures 16 and 17. These are summarized in the central columns of Tables 8 and 9.

On both experimental series, the outside incident pressure waves were atypical (see last records in Figures 16 and 17). The Series I wave reached 47.2 psi in 74 msec after an early-rising phase and the positive phase endured for 318 msec. The Series II overpressure pulse reached 91.9 psi in 64 msec and endured for 369 msec. The pressure parameters inside the structures depended upon whether the shelter filled through the escape hatch (slow-fill side) or the main entryway (fast-fill side). Pertinent data are summarized in Table 10.

TABLE 10

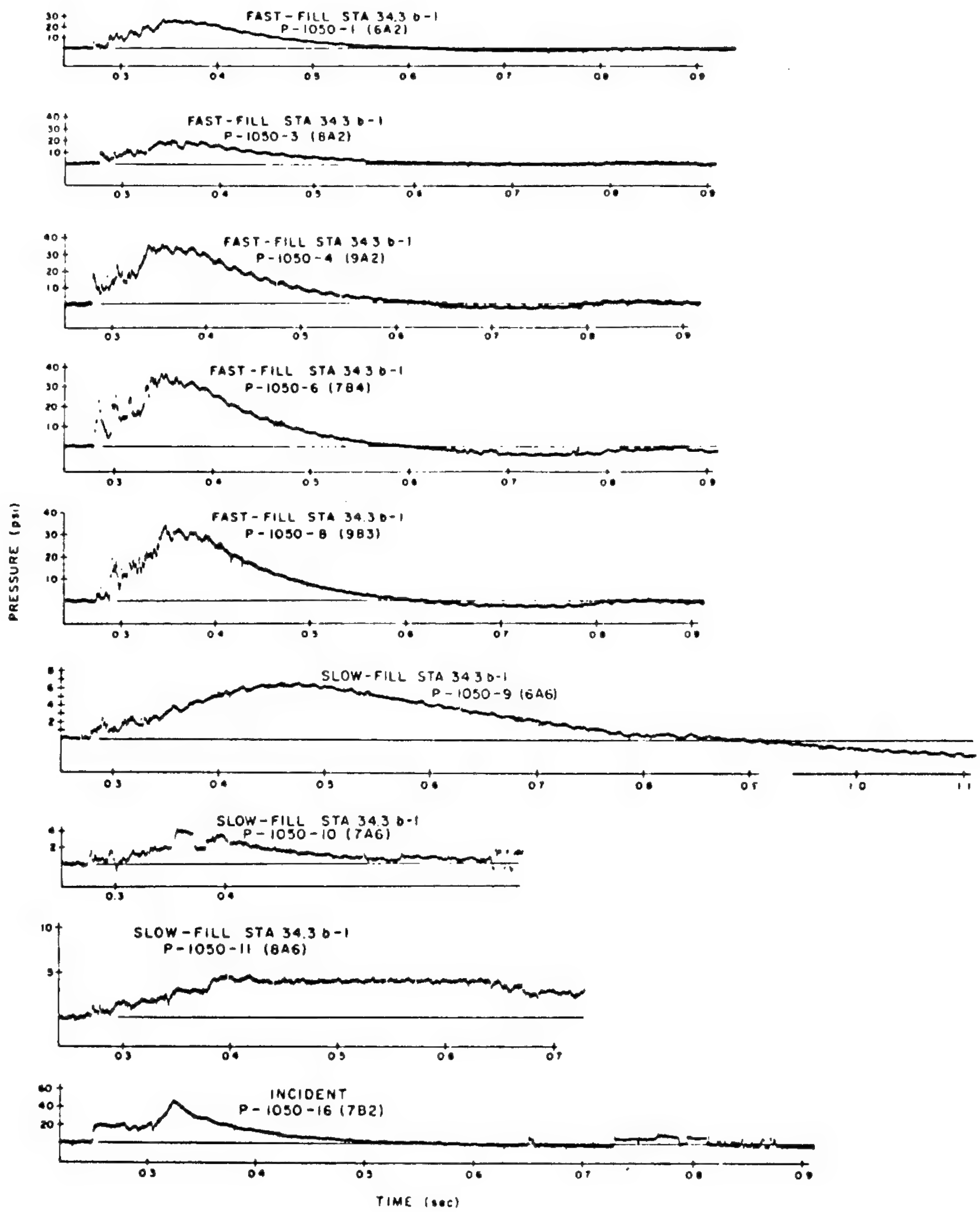
SUMMARY: AVERAGE PRESSURE-TIME DATA FOR GROUP SHELTERS[4,8]

Experimental Series	Shelter Room	Internal P_{max} psi (Average)	Arrival to P_{max} msec (Average)	Pressure Rise Rate psi/sec (Average)
I	Slow fill	6.7	206	33
	Fast fill	33.8	69.2	488
II	Slow fill	22.0	126	175
	Fast fill	66.6	99	673



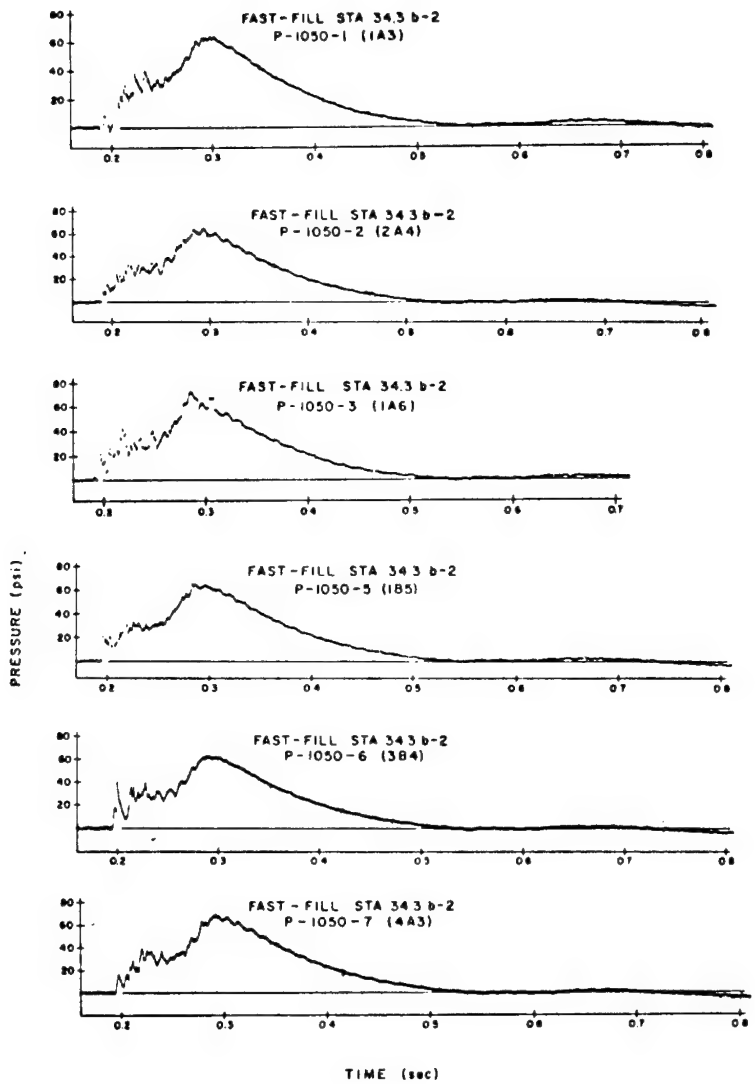
Plan view of partitioned group (blast biology) shelter[4,8]

Figure 15



Pressure-time records inside and outside the group shelter on Series I experiment[8]

Figure 16



Pressure-time records inside and outside the group shelters on Series II experiment[8]

Figure 17
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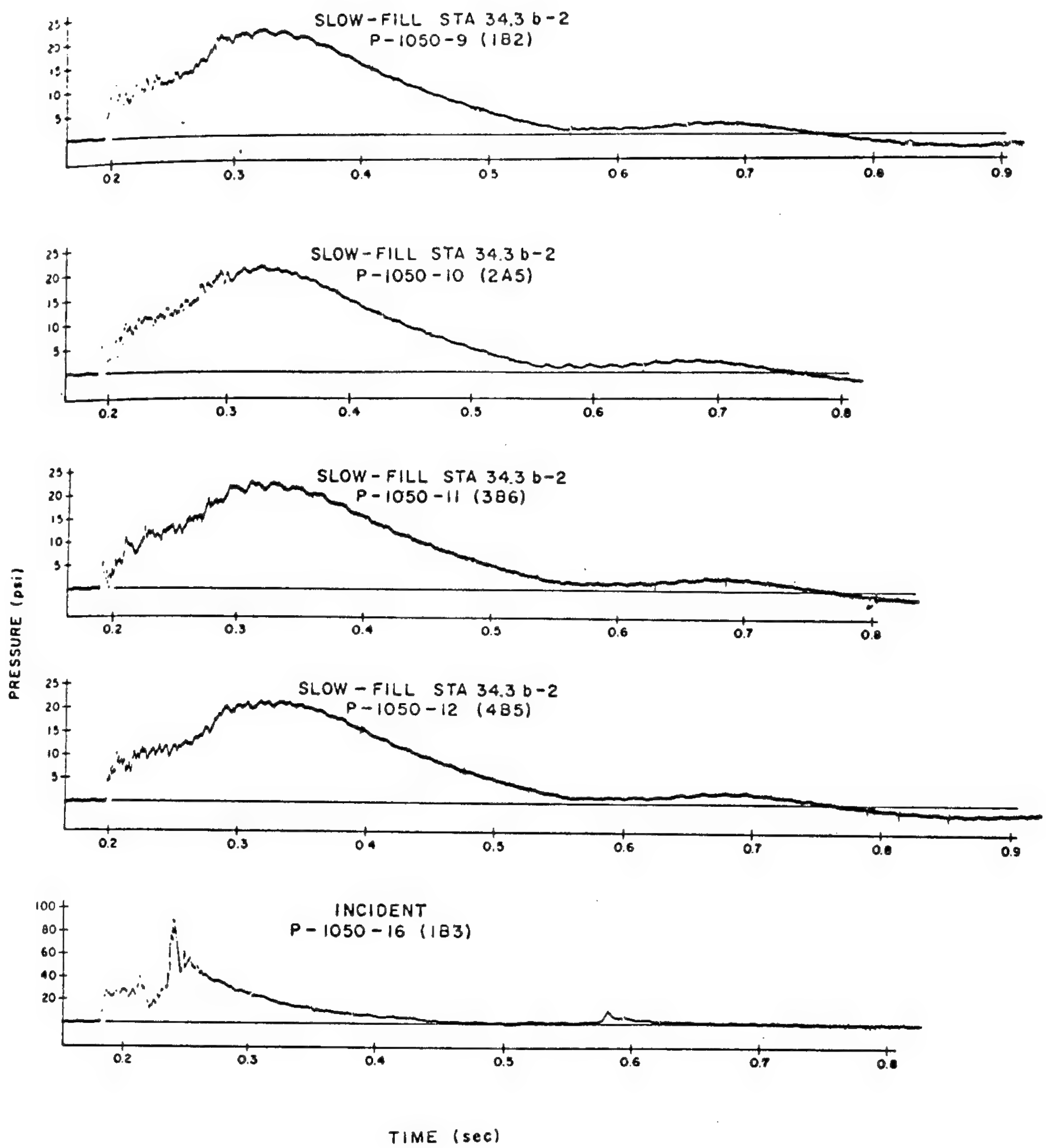

Figure 17

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TABLE 8

SUMMARY OF PRESSURE ENVIRONMENT AND RELATED PATHOLOGY IN GROUP SHELTERS

Experiment I[4]

Experimental Series	Shelter	Gauge designation	Distance from Ground Zero, ft	Max. internal over-press., psi	Time, msec Arrival to peak press.	Time, msec Over-press. duration	Max. internal neg. press., psi	Time to max. neg. press., msec	No. of animals	Animal designation and location	Gross pathology
I	Group slow-fill chamber	A-9	1050	6.7	206.3	637.3	−2.7	1050.8	10 dogs	A-9-A to A-12-A	None
		A-10		2.05*	61.0	(Gauge read to 76 msec after arrival)			23 rabbits	Ceiling racks 1, 3, 6, 9, 10; Nos. 21, 23, 26 on table	1 of 5 had minor lung hemorrhage (petechiae); 11 of 24 usable eardrums ruptured (26%)
		A-11		5.14*	120.0	(Gauge read to 491.7 msec after arrival)					
		A-12		4.14*	67.7	(Gauge read to 164.7 msec after arrival					
			Average	6.7	206.3	(Questionable data not included)			24 guinea pigs	Ceiling racks 2, 5, 8, 12; Nos. 22, 24, 25, 27 on table	1 of 5 had minor lung hemorrhage (petechiae); 13 of 28 usable eardrums ruptured (46%)
									27 rats	Ceiling racks 4, 7, 11; Nos. 28, 34 on table	1 of 5 had minor lung hemorrhage (petechiae); 3 of 8 usable eardrums ruptured (38%)
									20 mice	Ceiling racks 1, 3, 6, 9, 10	3 of 5 had minor lung hemorrhage (petechiae)
											Sample of 5 animals of each species sacrificed immediately except for mice (all sacrificed)
I	Group fast-fill chamber	A-1	1050	26.6	85.0	371.3	−2.5	388.0	10 dogs	A-1 to A-8-B	1 displaced — mediastinal and lung hemorrhages, brachial plexis injury, bilateral conjunctivitis; 2 subcapsular splenic hemorrhages; 10 of 20 usable eardrums ruptured (50%)
		A-2		15.5*	21.7	(Gauge read to 20.4 msec after arrival)					
		A-3		35.0	45.3	324.1	−6.4	1460.4			
		A-4		36.3	74.0	626.3	−2.4	896.8			
		A-5		34.1*	73.5	(Gauge read to 75.5 msec after arrival)					
		A-6		36.9	68.1	328.2	−4.4	468.3			
		A-7		34.2*	62.3	(Gauge read to 66.2 msec after arrival)					
		A-8		34.4	73.4	591.9	−2.7	684.6			
			Average	33.8	69.2	448.3	(Questionable values not included)				

TABLE 9

SUMMARY OF PRESSURE ENVIRONMENT AND RELATED PATHOLOGY IN GROUP SHELTERS

Experiment II[4]

Experimental Series	Shelter	Gauge designation	Distance from Ground Zero, ft	Max. internal over-press., psi	Time, msec: Arrival to peak press.	Time, msec: Over-press. duration	Max. internal neg. press., psi	Time to max. neg. press., msec	No. of animals	Animal designation and location	Gross pathology
II	Group slow-fill chamber	Z-9	1050	22.3	130.8	563.3	-3.3	1465.3	10 dogs	Z-9-A to Z-12-B	1 minor lung hemorrhage; 2 hemorrhagic spleens (subcapsular); 1 mucosal tear of urinary bladder; 8 of 12 usable eardrums ruptured (40%)
		Z-10		21.5	139.3	568.1	-2.8	1451.0			
		Z-11		22.8	121.2	567.8	-3.3	1518.0			
		Z-12		21.4	111.8	569.8	-2.7	1492.6			
			Average	22.0	125.8	567.3					
									23 rabbits	Ceiling racks 1, 3, 6, 9, 10; Nos. 21, 23, 31 on table	1 severe lung hemorrhage; 3 minor lung hemorrhages; 18 of 25 usable eardrums ruptured (72%)
									22 guinea pigs	Ceiling racks 2, 5, 8, 12; Nos. 22, 23 on table	1 of 22 expired; 1 severe lung hemorrhage; 4 moderate lung hemorrhages (1 dead); 5 minor lung hemorrhages; 29 of 32 usable eardrums ruptured (91%)
									30 rats	Ceiling racks 4, 7, 11; Nos. 24, 30, BI, BII, BIII on table	3 minor lung hemorrhages; 6 of 8 usable eardrums ruptured (75%)
									20 mice	Ceiling racks 1, 3, 6, 9, 10, 13, 14	17 of 20 expired (85%); 5 severe, 9 moderate, 2 minor lung hemorrhages; 1 pulmonary congestion; 1 subcapsular hemorrhage at liver; 1 had petechiae in mediastinal fat; 1 had petechiae in meninges; 3 survivors, no pathology

(continued on next page)

Table 9 (continued)

Experimental Series	Shelter	Gauge designation	Distance from Ground Zero, ft	Max. internal over-press., psi	Time, msec: Arrival to peak press.	Time, msec: Over-press. duration	Max. internal neg. press., psi	Time to max. neg. press., msec	No. of animals	Animal designation and location	Gross pathology
II	Group fast-fill chamber	Z-1	1050	63.9	108.8	562.0	-3.9	1647.2	10 dogs	Z-1 to Z-8-B	1 fatality due to violent impact (Z-1); 2 others nonfatally displaced (Z-2 and Z-8-B); otherwise: 4 minor lung hemorrhages (Z-½, Z-3, Z-6, Z-8-B); 2 hemorrhagic spleens (Z-½, Z-8-B); 1 pneumothorax (Z-7); 1 had subendocardial petechiae (Z-½); 1 had mesenteric petechiae (Z-8-A); 1 leg fracture (Z-8-B); 10 of 12 usable eardrums ruptured (83%)
		Z-2		64.9	107.4	518.5	-6.0	1835.3			
		Z-3		73.2	90.1	572.3	-4.6	617.1			
		Z-4		67.2	102.5	565.6	-2.2	1172.1			
		Z-5		65.5	91.9	555.1	-5.2	1064.4			
		Z-6		63.6	95.6	546.3	-3.0	682.3			
		Z-7		68.0	96.1	569.0	-2.9	1340.9			
		Z-8		66.5	101.2	556.1	-3.2	1178.0			
			Average	66.6	99.2	555.6					
		Q-Z		12.7	2.2	(Read from smoothed curves)					
									4 rabbits	13-c, d 14-c, d	1 minor lung hemorrhage; 4 of 5 usable eardrums ruptured (80%)
									4 guinea pigs	13-b, e 14-b, e	2 minor lung hemorrhages; 5 of 5 usable eardrums ruptured (100%)
									4 rats	13-a, f 14-a, f	2 minor lung hemorrhages; eardrums not usable
									4 mice	13-g, h 14-g, h	1 fatality—moderate lung hemorrhage; 1 minor lung hemorrhage among 3 survivors

Dogs (66 in number) — see Figure 18 for exposure locations which were approximately the same for both the experimental series — and small animals (44 mice, 63 rats, 52 guinea pigs and 52 rabbits) were restrained either in cages or harness, exposed in the shelters and subsequently studied.[4] The postshot pathological findings are shown in Tables 8 and 9 in relation to the pressure-time data. Except for one death and other injuries due to translation following failure of the harness and restraints as will be mentioned later, there was no severe primary blast damage in dogs other than one pneumothorax (Z-7). Relatively minor to moderate injuries, however, were common. These included eardrum rupture, middle ear and sinus hemorrhage, slight pulmonary hemorrhage, splenic hemorrhage, subendocardial petechiae, mesentery petechiae and lacerations of the urinary bladder. Tables 11 - 14 summarize all the dog findings and note the increase of singeing and skin burns that will be alluded to later.

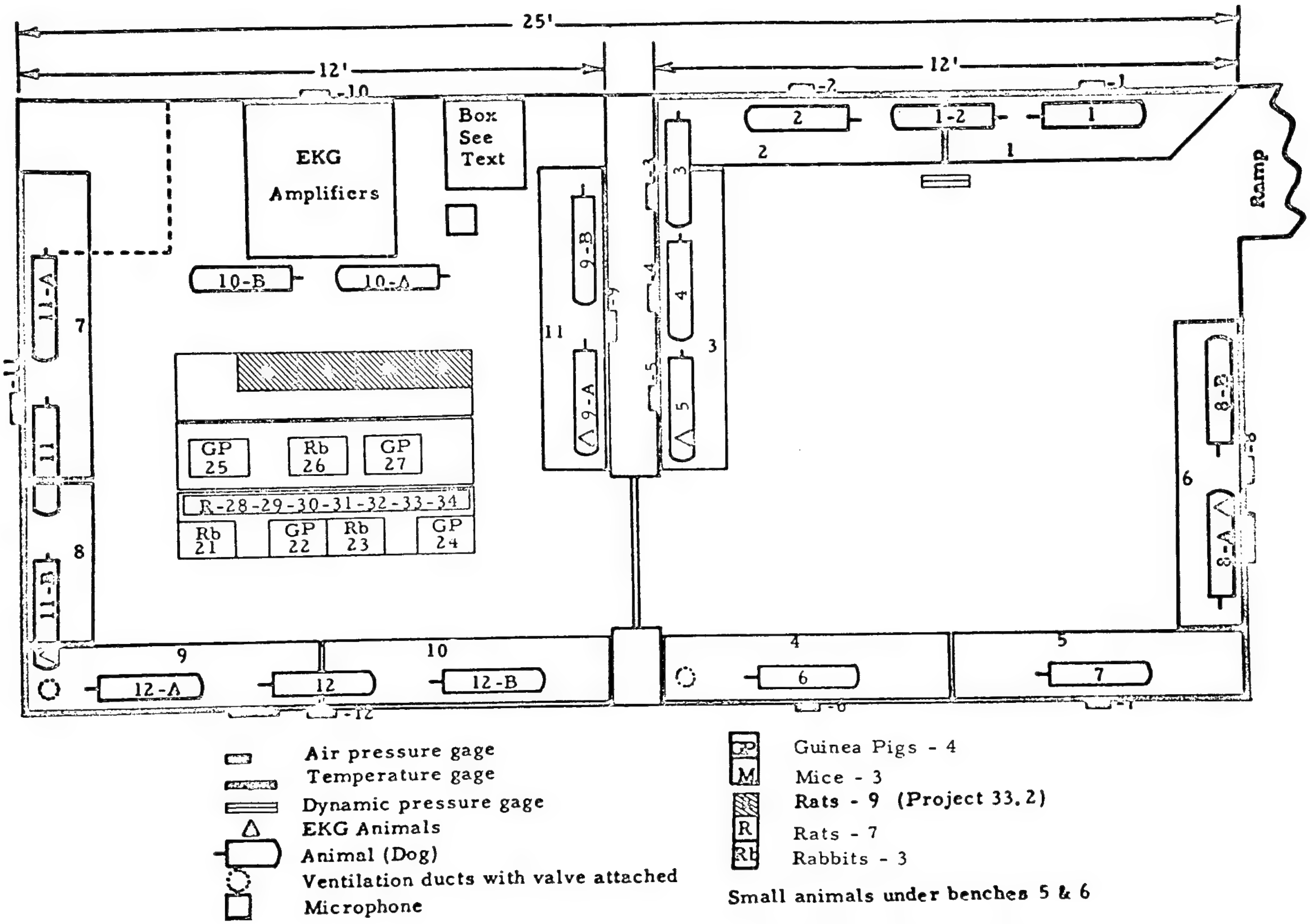
Also worthy of comment was the loss of 85 per cent of the mice exposed in the slow-fill side of the Series II group shelter. This was a puzzling matter since a maximum pressure of 22 psi slowly rising to its peak was not viewed as hazardous for mice. The occurrence of fast, transient, pressure spikes, the true magnitude of which were unrecorded by the relatively "slow" wall gauges, were thought to have been responsible for the lethality, an opinion that current knowledge encourages one to still regard favorably.

3. The 1957 Shelters

In 1957 the group shelters referred to above were again employed "open" for primary blast animal experiments on two shots.[5] In addition, other studies were carried out in "closed" underground structures.[6] These will now be noted briefly.

The Group Shelters — (Open)

The group shelters[5] for the 1957 operation were designated Structures 8001 and 8002. Pressure and "Q" gauges were installed by the Ballistics Research Laboratory. A circular, aerodynamic mound with a 3-ft diameter, round opening at the top was constructed over the



Partitioned group shelter. Animal location, except for those animals on the table, was the same for both experiments. (Benches were numbered 1 to 14; air bottles were located beneath the benches; fans were under benches 4 and 9; and heaters were under benches 4 and 8.)[4]

Figure 18

TABLE 11

INTERNAL PARENCHYMAL LESIONS IN DOGS

SERIES II[4]

Location	Animal* No.	Animal* Weight, lb	Peak static wall pressure, psi	Lung hemorrhage Right	Lung hemorrhage Left	Splenic hemorrhage	Laceration of urinary bladder	Other
Group shelter fast-fill chamber	Z-1	53	63.9	++	+++	++	++	(See text)
	Z-½	54			+	+	+	Subendocardial petechiae
	Z-2	55	64.9					
	Z-3	39	73.2		+			
	Z-4	36	67.2					Tracheitis
	Z-5	38	65.5					
	Z-6	45	63.6	+	+			
	Z-7	45	68.0					Left pneumothorax tracheobronchitis
	Z-8-A	54	66.5					Petechiae in mesentery
	Z-8-B	50		+		+	+	Leg fracture
Group shelter slow-fill chamber	Z-9-A	40	22.3					
	Z-9-B	35						
	Z-10-A	44	21.5					
	Z-10-B	43					+	
	Z-11-A	33						
	Z-11	31	22.8	+				
	Z-11-B	33						
	Z-12-A	51				+		
	Z-12	47	21.4			+		
	Z-12-B	36						
Basement exit shelter								
Closed	C-1	44	71.6				+	
	C-1-0	55						Bronchitis
Open	C-2	33	85.8	++	++	+	+	Subendocardial petechiae
	C-2-0	36		++	++			Subendocardial petechiae; left extradural hemorrhage
Closed	D-1	39	18.5					
	D-1-0	35						
Open	D-2	48		+	+		+	
	D-2-0	38		+++	++			Blood in bronchi
Utility shelter	U-22-A	36		+				
	U-22-B	48	(Death due to strangulation)					Subendocardial petechiae
	U-27-A	38	4.3					
	U-27-B	39						
	U-37-A	59	2.6					
	U-37-B	34						
Ranch dwelling bathroom shelter	Bth-A	37	1.3					
	Bth-B	56						
Brick house lean-to shelter	Lt-A	45	4.6					
	Lt-B	45						
Frame house corner shelter	Cor-A	34	3.7					
	Cor-B	35						

*See the first footnote in Table 12.

TABLE 12

NONPARENCHYMAL LESIONS IN DOGS, SERIES II [4]

Location	Animal* No.	Hair singeing	Skin burns	Ears† Right	Ears† Left	Intact right ear plug	Other
Group shelter fast-fill chamber	Z-1	+++	+++	+	+		Fatality (see text)
	Z-½	++	++	+‡	+‡		Bilateral conjunctivitis
	Z-2	+	++	+	+		
	Z-3	+		+		+	
	Z-4	+		+‡	+‡		
	Z-5	+		+	+		
	Z-6	++		+, h	+, h	+	
	Z-7	++	+	+‡	+‡	+	
	Z-8-A	++		+‡	+‡	+	
	Z-8-B	++	+	h	+, h		Fracture, left femur
Group shelter slow-fill chamber	Z-9-A	+					
	Z-9-B			+	+		
	Z-10-A	+	+	+	+		
	Z-10-B	+++	++			+	
	Z-11-A	++					
	Z-11	+			+, h	+	
	Z-11-B	+					
	Z-12-A	+			+		
	Z-12	+			+, h		
	Z-12-B	++	+	h	+, h		
Forward basement exit shelter Closed	C-1	+++	++	+	+		
	C-1-0			+‡	+	+	Hemorrhage, left frontal sinus
Open	C-2	+++	+++	+	+	+	Bilateral hemorrhage, frontal sinus
	C-2-0	+++	++	+, h	+, h		Bilateral hemorrhage, frontal sinus
After basement exit shelter Closed	D-1			+, h	h	+	
	D-1-0			h	+		
Open	D-2	++	+	+, h	h		Bilateral hemorrhage, frontal sinus
	D-2-0	++	+	+, h	+, h	+	
Utility type shelter	U-22-A						Hemorrhage, left frontal sinus
	U-22-B	(Death due to strangulation)					Bilateral hemorrhage, frontal sinus
	U-27-A						
	U-27-B					+	
	U-37-A						
	U-37-B						
Ranch dwelling bathroom shelter	Bth-A						
	Bth-B						
Brick house lean-to shelter	Lt-A						
	Lt-B			+			
Frame house corner shelter	Cor-A						
	Cor-B						

* As in Series I, the numbered designation of the animal corresponds to the similarly numbered adjacent pressure gauge in the group shelter. Where the suffix letters A and B are used, the animals are paired on either side of the gauge. Note the positions in Fig. 18. In the basement exit shelters the single-numbered animal, such as C-1-0, was positioned nearest the opening, whereas the companion dog (C-1) was placed in the rear of the shelter. In the remaining installations, the paired animals were suffixed with the letter A or B according to front or rear position, respectively, on either side of the gauge.

† +, perforation in tympanic membrane; h, focal hemorrhage in eardrum or in inner ear; conjunctivitis also seen in C-2 and D-2.

‡ Indicates doubtful data, from specimens available in laboratory, months after shot as a result of accidental damage during removal or loss.

TABLE 13

INTERNAL PARENCHYMAL LESIONS IN DOGS

SERIES I[4]

Location	Animal* No.	Animal* Weight, lb	Peak wall over-pressure, psi	Lung hemorrhage Right	Lung hemorrhage Left	Spleen hemorrhage	Other
Group shelter fast-fill chamber	A-1†	56	26.6	+		+	(See text)
	A-½†	39					
	A-2†	34					
	A-3†	35	35.0			+	Omental petechiae
	A-4†	44	36.3				Petechia in pericardial fat
	A-5†‡	37					
	A-6†	37	36.9				
	A-7†	40					
	A-8-A†‡	52	34.4				Pericardial petechiae
	A-8-B†	41					
Group shelter slow-fill chamber	A-9-A‡	37	6.7				
	A-9-B	48					
	A-10-A	43					
	A-10-B	38					
	A-11-A	53					
	A-11	45					
	A-11-B‡	38					
	A-12-A	57					
	A-12	56					
	A-12-B†	52					
Basement exit shelter							
Closed	B-1-A†	48	11.5				
	B-1-B†	48	13.5				
Half-open	B-2-A†	35	38.6				
	B-2-B†	34	47.0				
Open	B-3-A†	42	38.6				
	B-3-B†	45	43.1				

*The animal number corresponds to the similarly numbered adjacent pressure gauge in the group shelter. The suffix letters A and B are used to indicate that the animals were paired on either side of the gauge (Fig. 18). In the basement exit shelter the paired animals are suffixed with the letters A and B according to front or rear position, respectively, on either side of the gauge.

†Animals sacrificed immediately; A-11-A and other dogs were sacrificed 14 to 16 days postshot.

‡EKG.

TABLE 14

NONPARENCHYMAL LESIONS IN DOGS

SERIES I [4]

Location	Animal No.*	Hair singeing	Skin burns	Ears† Right	Ears† Left	Intact right ear plug	Other
Group shelter fast-fill chamber	A-1	+		+,h	+,h	+	Mediastinal and lung hemorrhages; bracheal plexis injury; bilateral conjunctivitis
	A-½	+			h	+	
	A-2	+		+	h	+	
	A-3	+		+	+,h	+	
	A-4	+		+,h	+,h		
	A-5	+		+,h	+,h		
	A-6			+	h	+	
	A-7	+		h			
	A-8-A					+	
	A-8-B			h		+	
Group shelter slow-fill chamber	A-9-A					+	
	A-9-B						
	A-10-A					+	
	A-10-B					+	
	A-11-A					+	
	A-11					+	
	A-11-B						
	A-12-A						
	A-12						
	A-12-B					+	
Basement exit shelter							
Closed	B-1-A	+					
	B-1-B					(?)	
Half-open	B-2-A	+++	++		+,h		
	B-2-B	+		+			Hemorrhage, right frontal sinus
Open	B-3-A	+++	+	+	+		
	B-3-B	+				+	

*See the first footnote in Table 13.

†+, Perforation of tympanic membrane; h, Focal hemorrhage.

3-ft-square escape hatch of each shelter. See Figure 19. This was left open for one shot (8001), but was covered with a 4-layered plate 1/2 in. thick with matching holes 1/4 in. in diameter. The sieve plate contained 23 per cent open area (1.63 sq ft) compared with the unscreened 3-ft orifice.

Pressure-time data, reproduced from the records of flush-mounted, self-recording wall gauges, are shown in Figure 20 for the 8001 and Figure 21 for the 8002 structure. A comparison of the internal pressure records with those recorded outside are shown in Figure 22* and 23.* The pressure-time data are given in Table 15 for all gauges and their relation with the animal stations are shown in Figures 24 and 25. All animals were restrained to avoid translational effects except for certain dogs which will be discussed later.

Pathological findings postshot are noted in Tables 16 and 17. These were generally similar to, though less severe than those noted in the group shelters in 1955 and are included for completeness as well as for those interested in minimal pressure conditions for biological damage. The translational and thermal problems encountered will be discussed later.

The French and German Shelters (Closed)

Also, in 1957, 20 caged mice were placed in 12 underground structures on one event to help assess shelter performance biologically.[6] Free-field incident overpressures ranged from 175 to 7.2 psi.[9] Inside pressures as far as measurements were concerned were documented at 0.2 to 14.4 psi as noted in Table 18 wherein the biological observations are also summarized.

4. The Underpressure

No attempt will be made here to document the magnitude of the underpressure that usually follows the overpressure component

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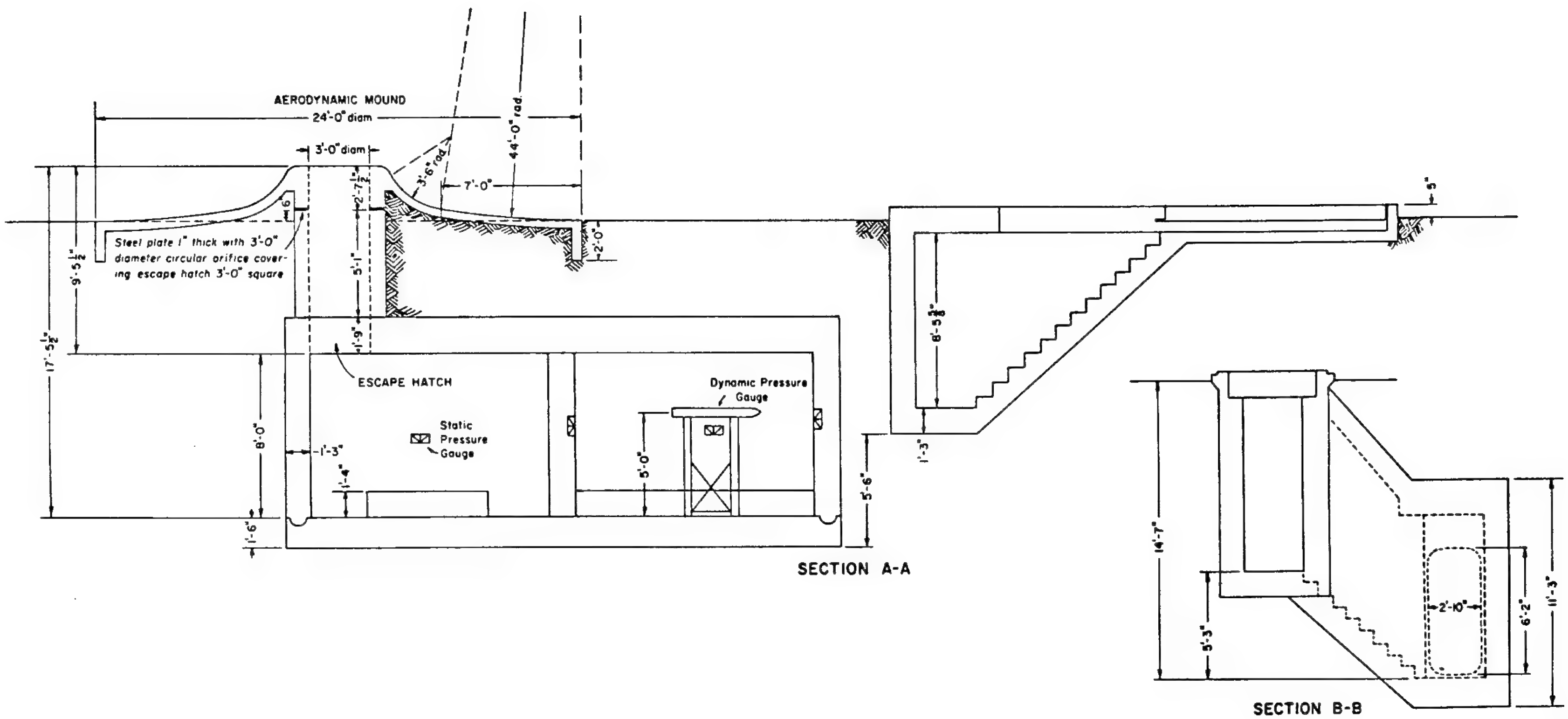
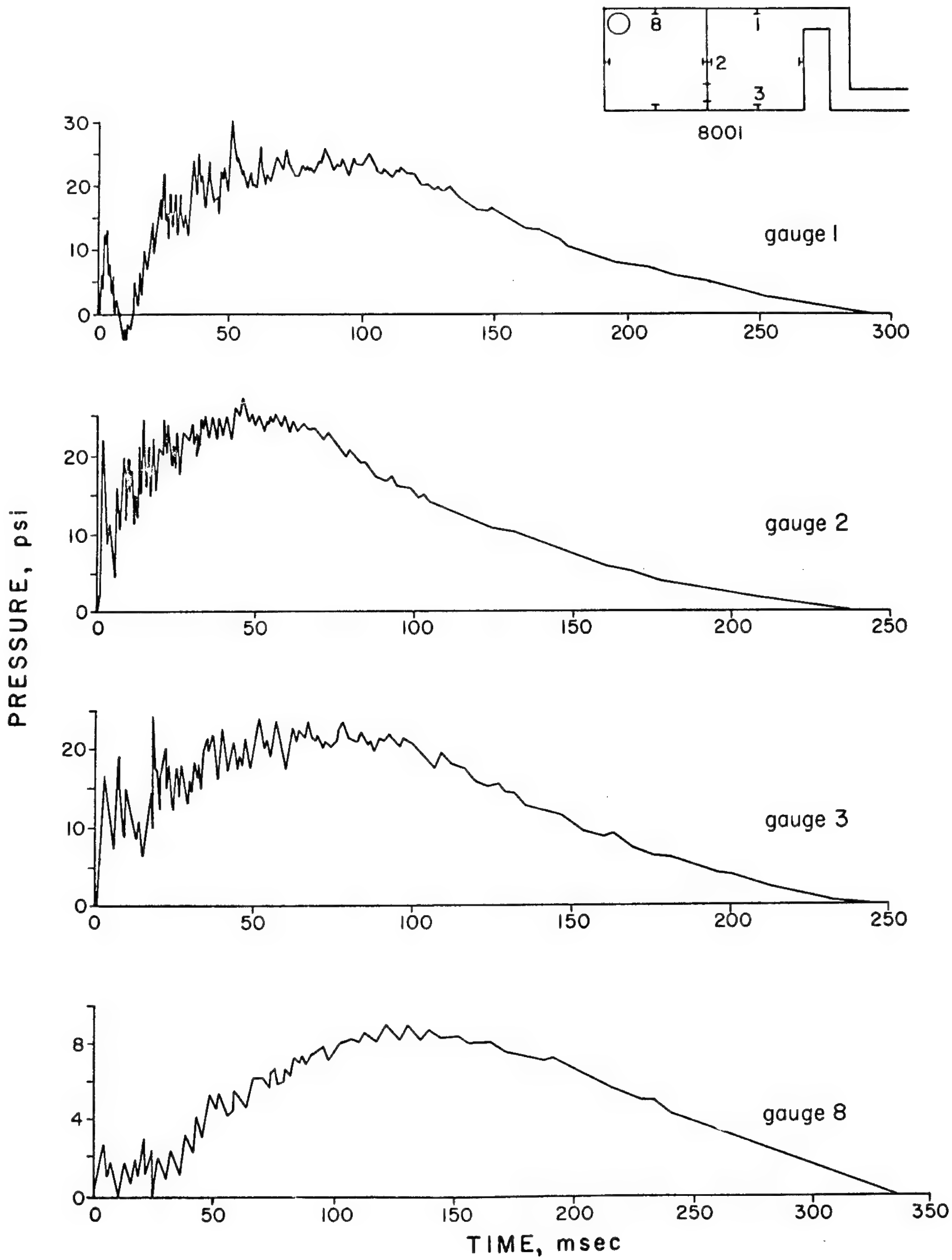
*See References 5 and 18 for details concerning the approach of Clark and Reference 8 for the work of Vortman for predicting the pressure occurring inside the shelter.



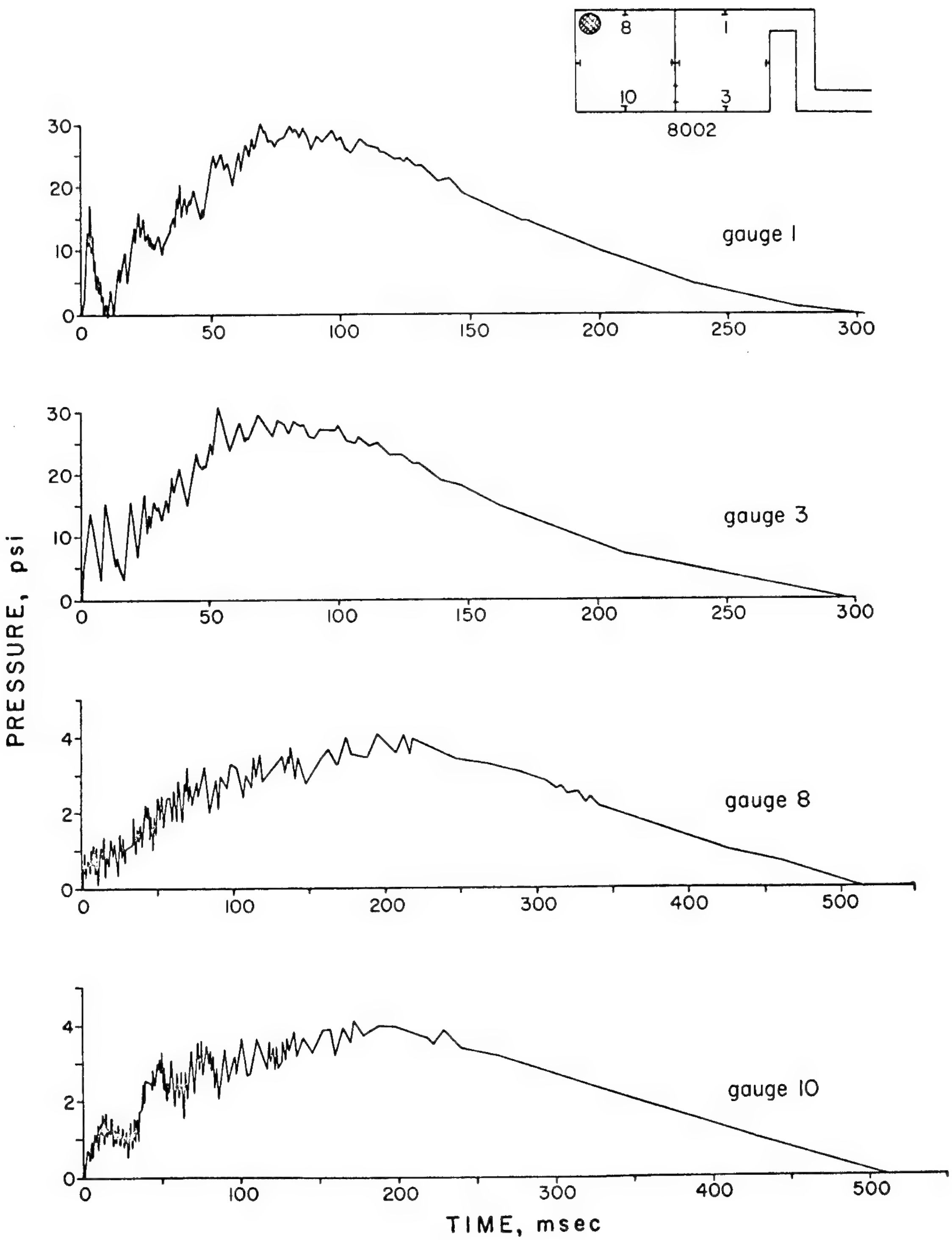
Section of underground shelter 4-33.1-8001.[5]

Figure 19



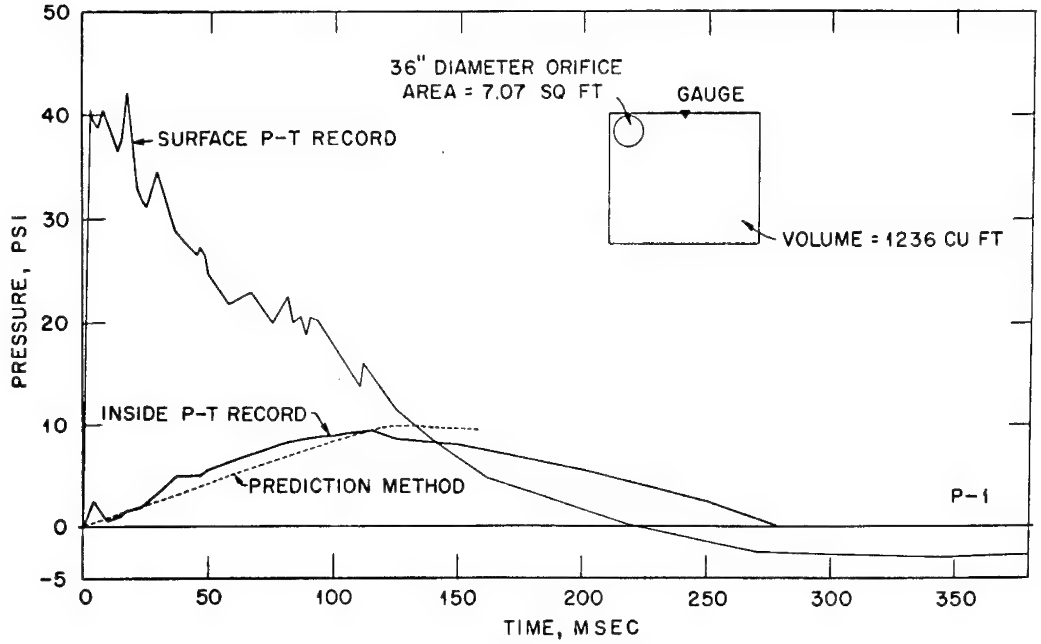
Pressure-time curves as recorded inside shelter 8001.[5]

Figure 20

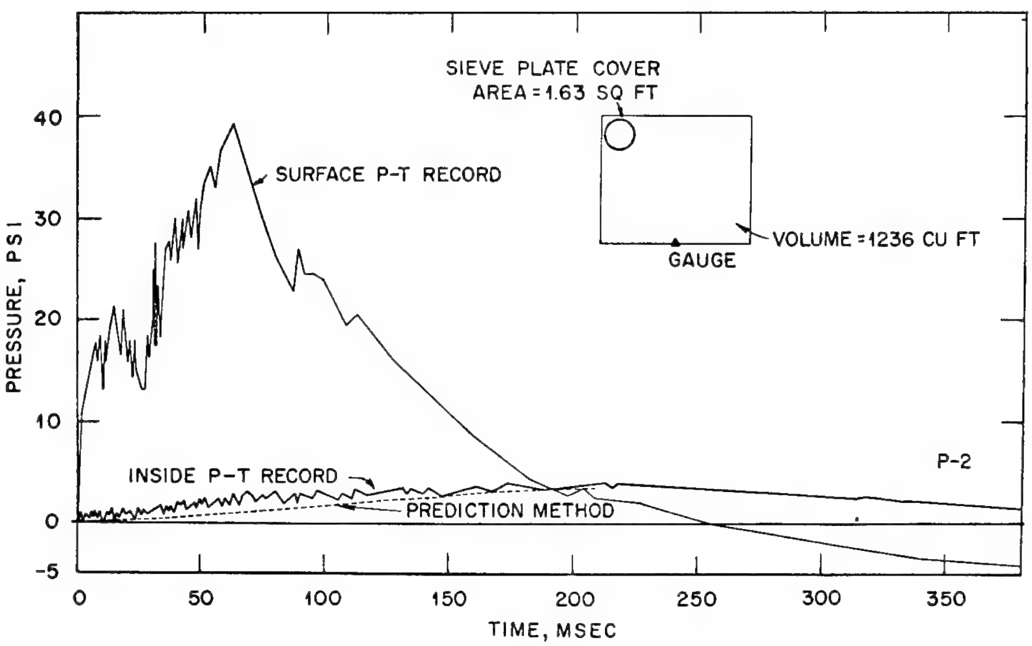


Pressure-time curves as recorded inside shelter 8002.[5]

Figure 21

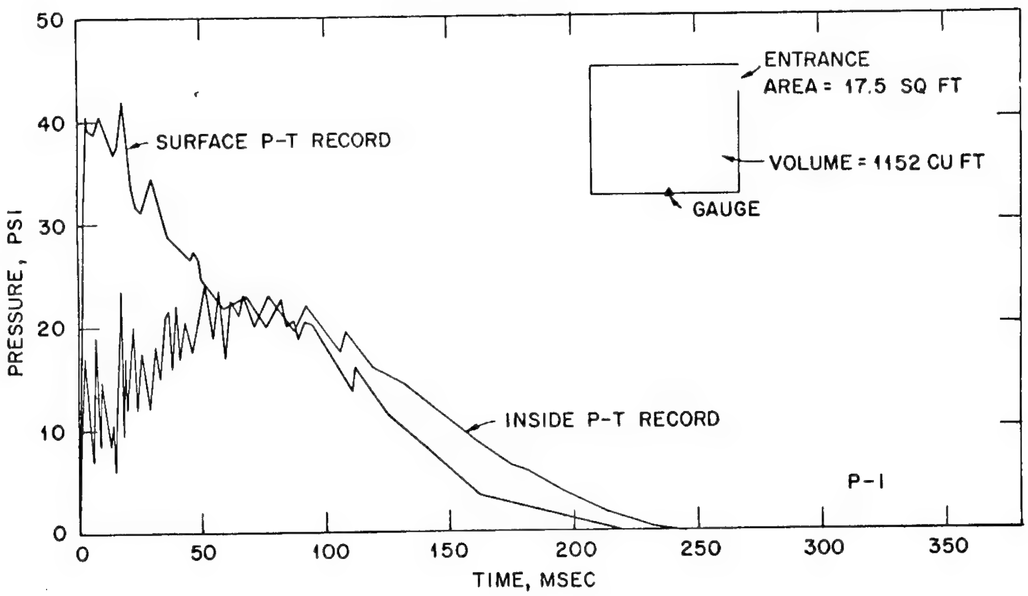


Graph comparing the pressure-time recorded outside, within, and that predicted for inside the slow-fill chamber of shelter 8001.[5]

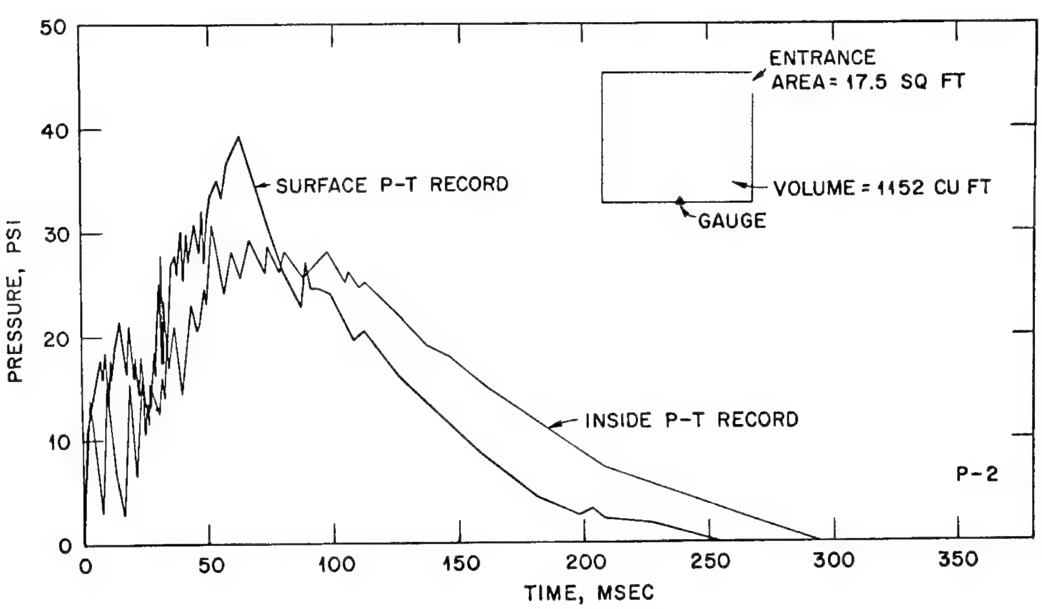


Graph comparing the pressure-time recorded outside, within, and that predicted for inside the slow-fill chamber of shelter 8002.[5]

Figure 22



Comparison of the pressure-time recorded outside and within the fast-fill chamber of shelter 8001.[5]



Comparison of the pressure-time recorded outside and within the fast-fill chamber of shelter 8002.[5]

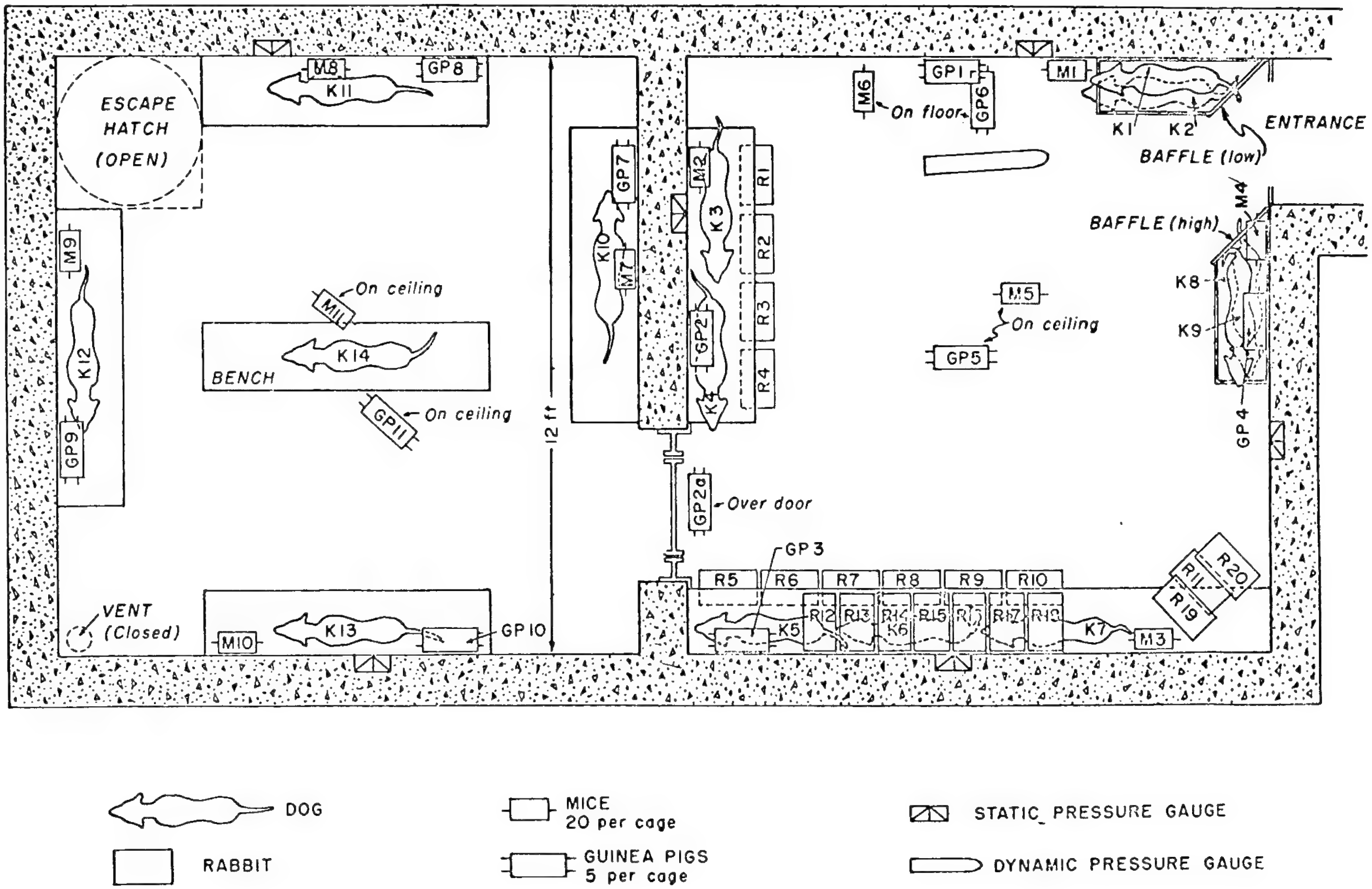
Figure 23

TABLE 15

PARAMETERS OF THE BLAST WAVE INSIDE SHELTERS 8001 AND 8002[5]

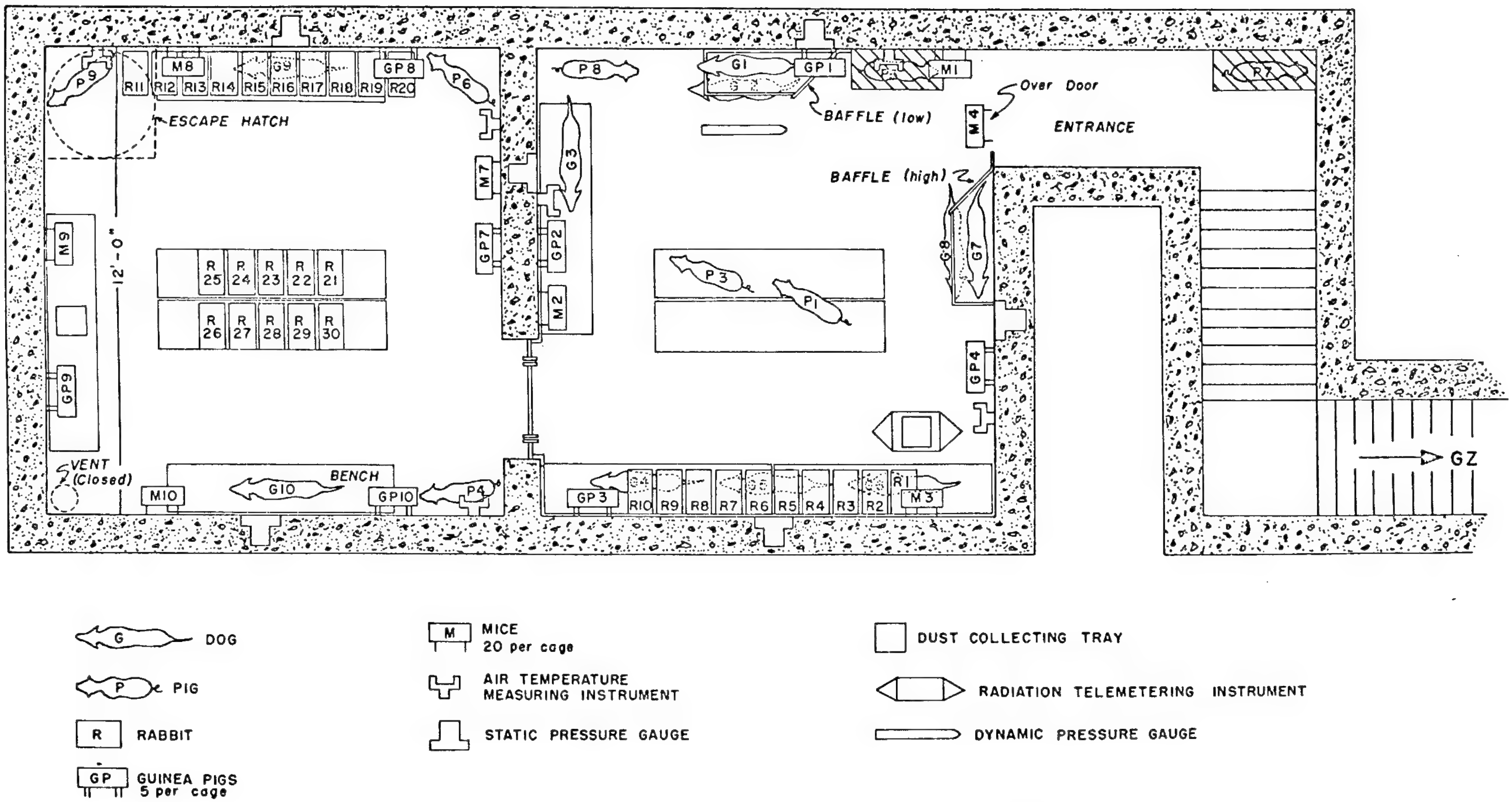
Gauge location	Peak over-pressure, psi	Time to peak pressure, msec	Duration of positive phase, msec	Peak negative pressure, psi	Time to peak negative pressure, msec	Duration of entire wave, sec
Structure 8001						
Fast-fill						
Wall 1	25.7	51	292	−3.4	406	2.32
Wall 2	27.0	45	240	−3.5	354	2.71
Wall 3	23.8	50	245	−6.3	399	2.66
Wall 4	25.6	66	297	−3.2	420	2.60
Average	25.5	53	269	−4.09	394	2.58
Q_1*†	10.5					
Slow-fill						
Wall 8	9.0	119	330	−3.01	472	2950
Wall 10†	10.0					
Average	9.5					
Structure 8002						
Fast-fill						
Wall 1	30.4	68	305	−3.5	464	3.44
Wall 2‡	30.2	59				
Wall 3	30.5	68	294	−3.3	403	
Wall 4†	30.0					
Average	30.3	65	300			
Q_2§	2.0					
Slow-fill						
Wall 8	4.1	194	517	−2.3	1097	3.42
Wall 10	4.1	212	506	−2.3	1254	3.19
Average	4.1	203	512	−2.3	1176	3.31

*Located 5 ft from main doorway, 5 ft above floor, and 2 ft from wall 1 (parallel with wall).
†Peak pressure only.
‡Peak pressure and time only.
§Located 7 ft from main doorway, 5 ft above floor, and 2 ft from wall 1 (parallel with wall).



Location of animals and instruments in shelter 8001.[5]

Figure 24



Location of animals and instruments in shelter 8002.[5]

Figure 25

TABLE 16

SUMMARY OF PATHOLOGICAL FINDINGS FOR ANIMALS EXPOSED IN SHELTER 8001[5]

Species	Number of animals autopsied*	Peak pressure, psi	Duration of overpressure, msec	Pathological remarks
Fast-fill				
Dog	8	25.7 27.0 23.8 25.6	292 240 245 297	No canine mortality; K-1 severely injured from impact, see text for details; K-1, K-3, and K-9 had petechial hemorrhages in lungs; 8/16 readable eardrums ruptured (50%)
Average		25.5	269	
Rabbit	20			No mortality; 5 with slight lung hemorrhages (Nos. 1, 2, 13, 14, and 15); 39/40 eardrums ruptured (97.5%)
Guinea pig	35			Two killed: 3-1 and 6-3; 5 others with lung hemorrhage (Nos. 2a-5, moderate; 2-2, 2-3, 3-3, and 3-4, slight); 52/52 eardrums ruptured (100%)
Mouse	60			Mortality: 1 from cage 1 and 2 from cage 2; 16 cases of lung hemorrhage (10 from cage 2, 2 from cage 4, and 4 from cage 5); ears not assessed
Slow-fill				
Dog	4	9.0 10.0	330	No significant pathology; 0/10 eardrums ruptured (0%)
Average		9.5		
Guinea pig	25			One slight lung hemorrhage (No. 11-4); 38/44 eardrums ruptured (86.4%)
Mouse	50			No pathology; ears not examined

*In addition, 110 mice (10 from each cage) and 1 dog from each chamber (K-8 and K-14) were observed for possible radiation effects for 30 days postshot.

TABLE 17
SUMMARY OF PATHOLOGICAL FINDINGS FOR ANIMALS EXPOSED IN SHELTER 8002[5]

Species	Number of animals autopsied*	Peak pressure, psi	Duration of overpressure, msec	Pathological remarks
Fast-fill				
Dog	8	30.4	305	No mortality; G-1 burned and G-2 and G-5 singed slightly; G-4 slight lung hemorrhage and nasal sinus hemorrhaged; 12/16 eardrums ruptured (75%)
		30.2		
		30.5	294	
		30.0		
Average		30.3	300	
Rabbit	6			No mortality; two slight lung hemorrhages (Nos. 8 and 10); 6/10 eardrums ruptured (60%)
Guinea pig	12			No mortality; all animals in cages 1 and 2 were singed; 8 animals exhibited lung hemorrhage (3 from cages 2 and 4, 2 from cage 3); 24/24 eardrums ruptured (100%)
Mouse	60			Mortality: 14 from cage 1 and 1 from cage 2; the 15 dead mice had lung hemorrhage, also 4 of cage 1, 6 of cage 2, and 1 of cage 4; mice in cages 1 and 2 were burned
Pig	5			Mortality: No. 7; lung hemorrhage, No. 7, massive; No. 5, moderate; No. 3, slight; pigs 5 and 7 burned; 7/8 eardrums ruptures (87.5%)
Slow-fill				
Dog	2	4.1	517	No pathological lesions; 1/4 eardrums ruptured (25%)
		4.1	506	
Average		4.1	512	
Rabbit	10			No pathology except 2/19 eardrums ruptured (10.5%)
Guinea pig	12			No pathology; 0/24 eardrums ruptured (0%)
Mouse	40			No pathology; ears not examined

*There were 14 rabbits, 16 guinea pigs, 2 swine, and 60 mice saved for radiation effects.

TABLE 18

STRUCTURES IN WHICH 20 MICE WERE EXPOSED
IN THE SMOKY EVENT IN 1957[6, 9]

STRUCTURE DESIGNATION	GROUND RANGE IN FT	OUTSIDE INCIDENT P_{MAX} PSI	INSIDE P_{MAX} PSI	COMMENT
II-1	1005	116	0.3	None died
*II-2	1005	116	--	19 of 20 dead on recovery** (ionizing radiation)
II-3	1005	116	1.6	11 of 20 dead in 60 days
II-4	1005	116	14.4	13 of 20 dead in 60 days
II-5	1005	116	1.5	5 of 20 dead in 60 days
RAa	840	175	--	2 of 20 dead in 60 days
RAc	1005	116	0.2	1 of 20 dead in 60 days
CAb	1005	116	--	All dead on recovery** (CO poisoning)
RAd	1176	81	--	2 of 20 dead in 60 days
RCa	1770	26	0.5	1 of 20 dead in 20 days
RCb	2430	11.5	0.3	None died
RCc	4320	7.2	--	

*EXPOSED IN AN ENTRYWAY SHAFT WITH LITTLE SHIELDING FROM IONIZING RADIATION.
**RECOVERY ON D + 2.

NOTE: 1. NONE OF THE DELAYED LETHALITY WAS DUE TO IONIZING RADIATION; RATHER, IT WAS DUE TO A SALMONELLA INFECTION.
2. THERE WERE NO IMMEDIATE DEATHS NOR PATHOLOGY ATTRIBUTED TO BLAST IN ANY OF THE ANIMALS.

of a blast wave. That such occurs, however, must not be forgotten, for structural damage may be caused by the negative wave and biological events of consequence may be associated with the occurrence; viz., eardrum rupture and possibly sinus pathology and lesions of the lungs under certain conditions.

B. Transient Winds (Secondary and Tertiary Effects)

Pressure variations occurring inside structures can be accompanied by transient winds of high velocity particularly if there is a restriction to air flow into and out of a structure. Depending mostly upon the magnitude and duration of the wind velocity, but also often critically upon local conditions and the occurrence of areas of high turbulence, the winds may be hazardous for at least two reasons: viz., first, energy may be transferred to debris or other inaminate objects, and these, as missiles, may produce penetrating or non-penetrating injury (secondary effects); second, animate objects subjected to accelerative loading (that may or may not be hazardous), gain significant velocity, and damage, as a consequence of whole body displacement, may ensue (tertiary effects).

Also as will be noted later, blast-induced winds may carry dust, missiles and other undesirable debris and materials into a structure to the detriment of objects and inhabitants therein. Further, transient wind and pressure may "explode" or displace underdesigned air ducts and damage or destroy ventilating fans and devices. These matters place a premium either upon fast closure times of blast-protective valves or upon a means to preinitiate their function, for high velocity winds in air ducts can occur prior to valve closure even when the latter is measured in a few tens of msec.

Data selected from field experiences will now be noted to emphasize the few statements mentioned above.

1. Dynamic Pressure "Q" Measurements

Dynamic pressure measurements were made inside the shelters mentioned above on 3, 2 and 2 occasions in 1953, 1955 and 1957, respectively. Relevant data are shown in Table 19 along

TABLE 19

MAXIMUM PRESSURE AND "Q" DATA RECORDED INSIDE NEVADA SHELTERS[3, 4, 5, 8]

Test Year and Reference	Shelter Designation	External P_{Max} psi	Location of Gauge	Maximum Internal Dynamic Pressure (Q) psi	Comments
1953[3]	1-601	13.5 (atypical wave)	See Fig. 9	3.3	Standing anthropometric dummy violently displaced. Sitting dummy (side-on) displaced 4 ft.
	8-602	7.0 (atypical wave)	See Fig. 10	0.7	"Pendulum" dog reached about 6 ft/sec in 230 msec
	8-601	8.0 (atypical wave)	See Fig. 10	0.2	
1955[4, 8]	Group-I	47.2 (atypical wave)	See Fig. 18	12	Dog A-1 mediastinal and lung hemorrhage. Front leg paralysis (bronchial plexus injury).
	Group-II	91.9 (atypical wave)	See Fig. 18	12.7	Dog Z-1 violently impacted against wall 10 ft away — immediately fatal. Dog Z-2 and Z-8-B torn from restraints. Z-8-B fractured leg.
1957[5]	8001	42.1 (near typical wave)	See Fig. 24 5 ft inside door	10.5	Dog K-1 violently impacted against wall — fractured spine, severed spinal cord.
	8002	39.2 (atypical wave)	See Fig. 25 7 ft inside door	2.0	Dog G-1 translated across the shelter. No serious impact injury — slight lung hemorrhage, sinus hemorrhage.

with a few pertinent comments regarding effects that occurred near or in the vicinity of the "Q" gauges.

The 1953 Shelters

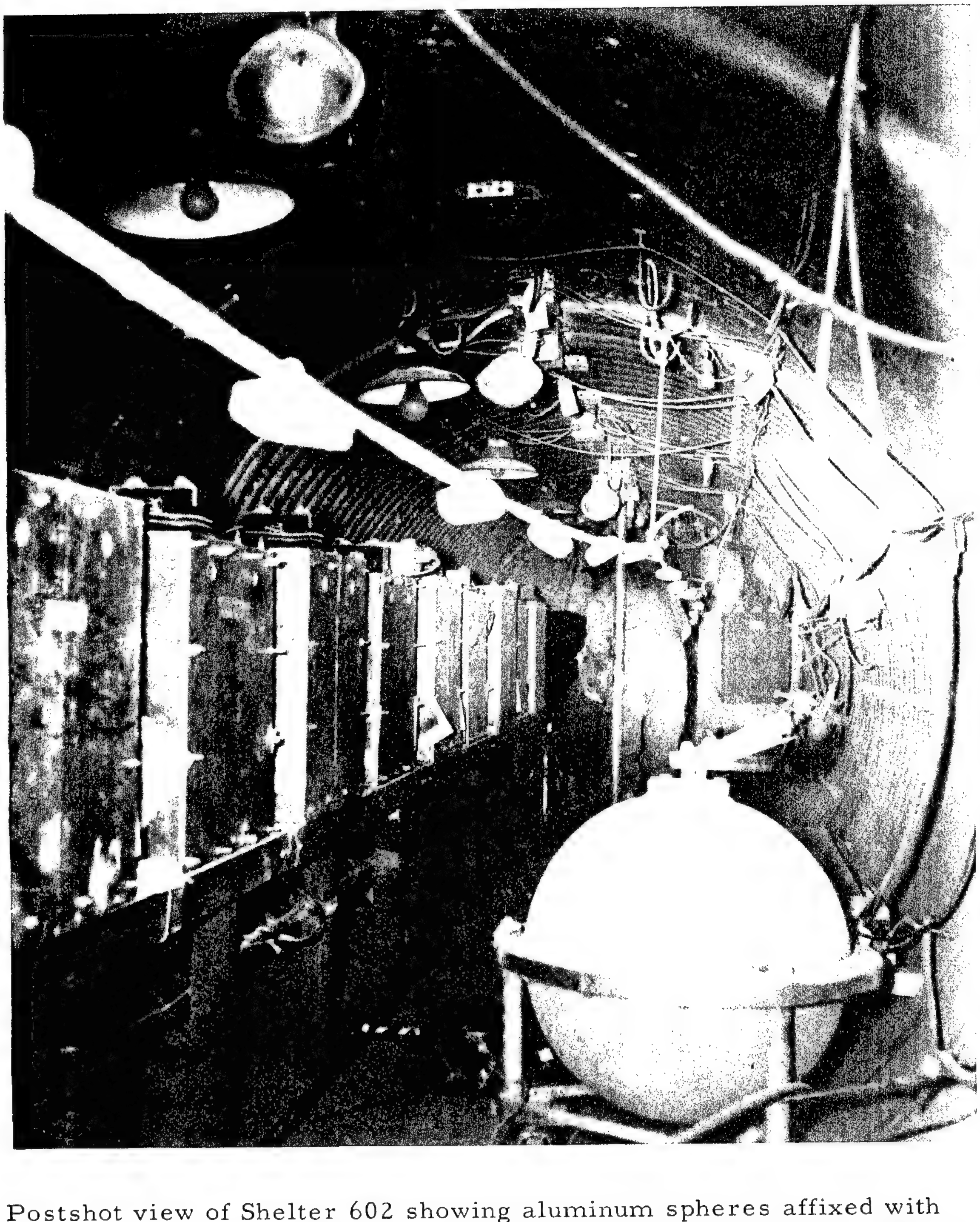
For example in the 1-601 shelter in 1953, the "Q" recorded was about 3.3 psi. Judging by the appearance of the shelter afterwards, the standing anthropometric dummy facing the blast was violently displaced. The eyebolts, to which the dummy's restraining cables were attached to keep the "creature" from impacting against equipment downstream, were badly bent.

Also, spheres were suspended from bolts affixed to the midline area of the ceiling of the shelter (see Figure 26). The bolt was bent sharply downstream, as shown by the postshot photo reproduced as Figure 27, by the force of the high transient winds playing over the sphere located a few feet just inside the door.

From unpublished work carried out by Clark and Crawford,[19] which included a determination of the force required to bend a similar bolt as much as that shown in Figure 27, and a reanalysis of the older data by Bowen and Fletcher,[20] it is probable that the maximum wind velocity impinging upon the bolt-sphere arrangement just inside the door was bout 422 mph. Also, it seems likely that the maximum wind velocity measured by the "Q" gauge 20 ft inside the main door into the shelter was close to 438 mph.

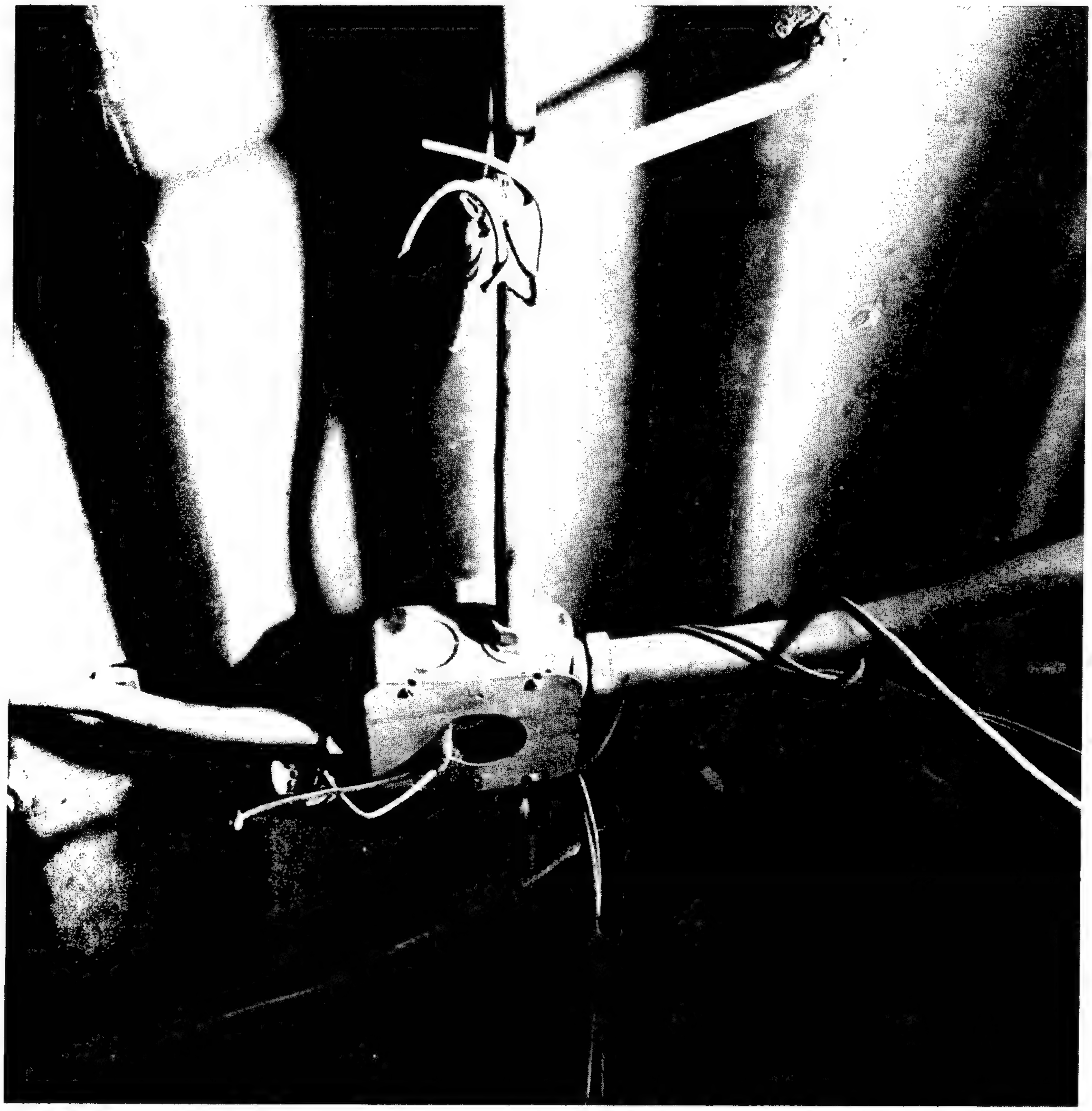
The 1955 Group Shelters

In 1955 one dog at the station near the entry into the "fast-fill" room, numbered 1 in Figure 18, was displaced by wind forces measured to have a maximum "Q" of about 12 psi by a gauge located nearby. On the second series, three dogs located at stations 1, 1-2, and 8B near the entryway as shown in Figure 18 were displaced. Dog Z-1, facing the wind, was torn out of a heavy harness fitted with "doubled up" snaps and violently impacted against the downstream wall. No doubt death occurred instanteaously. Figure 28 shows the postshot condition of the harness including a "blow-up" of one of the steel snaps and Figure 29 is a print of a postshot photo of the animal as seen by the early viewing party.



Postshot view of Shelter 602 showing aluminum spheres affixed with bolts to the ceiling (AEC Project 23.15, Lovelace Foundation, Unpublished.[19])

Figure 26



Postshot view of ceiling of Shelter 602 showing bolt bent by wind forces blowing against an aluminum sphere similar to those shown in Figure 26. The sphere had been removed from the bolt shown prior to taking this photograph (AEC Project 23.15, Lovelace Foundation, Unpublished.[19])

Figure 27

Close-up showing shear failure of Z-1 harness snap[4]

Z-1 harness, postshot[4]

Figure 28

Postshot view of floor of fast-fill compartment of Series II group shelter showing animal Z-1.[4]

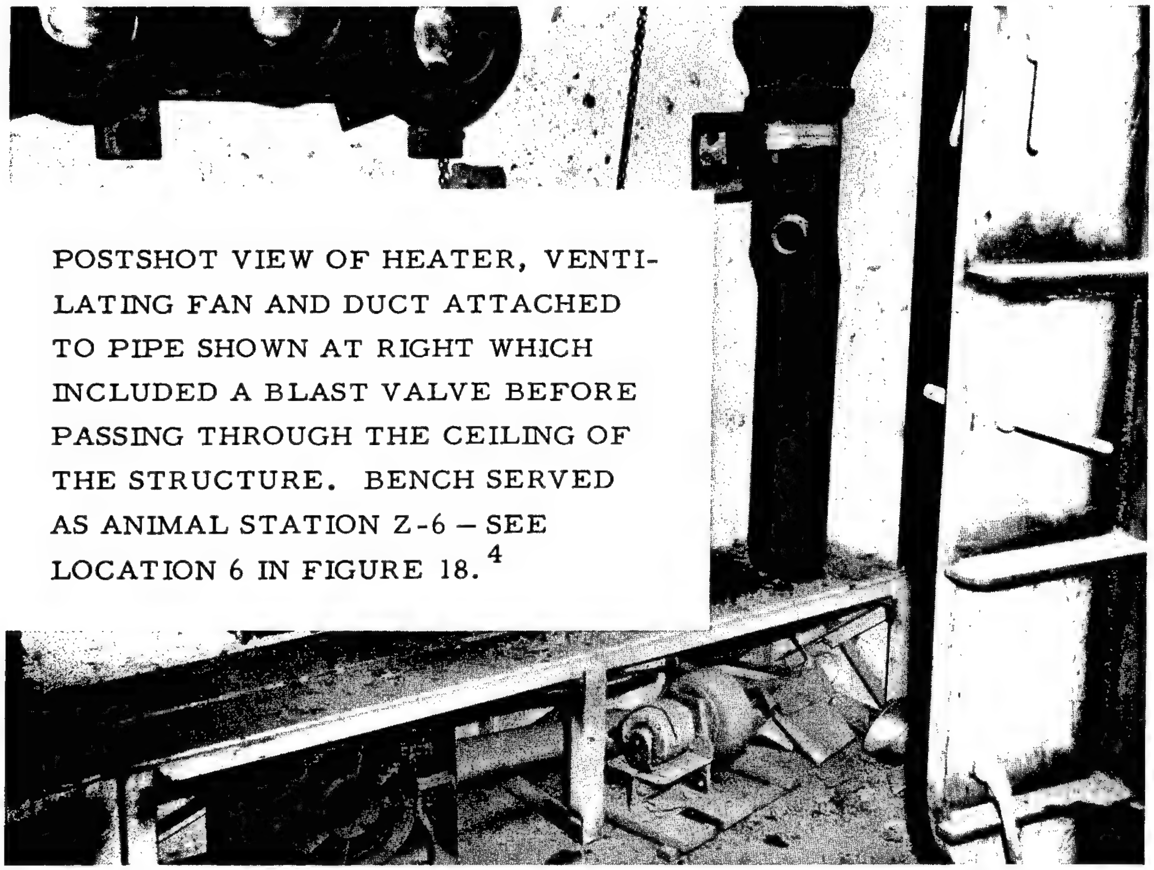
Figure 29

Among other things, Figure 29 shows a great deal of dust and debris, serving to emphasize the "dirty" nature and condition of the shelter after the shot. Also shown is a louvered, metal cover swept by the cyclonic-like winds from a heater located under bench No. 5 as shown in Figure 18. Figure 30, including the heater from which the cover came, a motor-driven fan and the remains of light ducting attached to the heavy inlet pipe coming from the ceiling, allows one to appreciate the shambles created by the blast-induced winds. In the case of the shelter in question, this is a remarkable fact mostly because the initial positive winds — those blowing into the shelter — only endured for about 0.1 second, the time it took the inside pressure to reach a maximum at which moment the internal pressure was equal to that outside the structure. After this, the initial negative winds — those blowing out of the shelter — endured for about 1.5 seconds,, a time closely related with the falling phase of the free-field pressure pulse. Subsequently, positive, and perhaps positive and negative winds in an oscillatory manner, probably occurred. Their magnitude and duration could be expected to be relatively low and long, respectively, but still might be significant depending upon the pressure differences involved, the area and shape of the entryway, and the volume of the shelter.

<u>The 1957 Group Shelter</u>

Table 19, including information about the group shelters in 1957,[5] shows on the one hand a maximum "Q" inside the shelters of 10.5 associated with an outside P_{max} of 42 psi. The "Q" value was close to those of 12 - 13 psi recorded in 1955 when the outside pressure was 47 and 92 psi. On the other hand in 1957, a "Q"$_{max}$ of 2 psi was recorded inside the structure when the outside P_{max} was 39.2. The probable reason for this is that the outside wave form was nearly "typical" for the 8001 structure, but "atypical" for the 8002 shelter.

Be this as it may, studies of the displacement potential of the winds were made in the two group shelters in 1957.[5] Animals were



POSTSHOT VIEW OF HEATER, VENTILATING FAN AND DUCT ATTACHED TO PIPE SHOWN AT RIGHT WHICH INCLUDED A BLAST VALVE BEFORE PASSING THROUGH THE CEILING OF THE STRUCTURE. BENCH SERVED AS ANIMAL STATION Z-6 – SEE LOCATION 6 IN FIGURE 18.[4]

Figure 30

mounted behind screens and baffles as shown in Figures 24 and 25, and exposed paired with other animals not so protected. Portions of the restraining leads for the harnessed and paired animals were replaced with string. Thus the animals located at floor level behind the screens or baffles and the animals mounted on a bench above were equally free to be "translated" if the drag force were sufficient to break the strings.

None of the four animals, two each in shelters 8001 and 8002, mounted behind the screens or baffles were translated. One facing the door, dog K-1 in Figure 24, was thrown violently against the opposite wall and suffered severance of the spinal cord when vertebral facture occurred. Figure 31 shows the fracture, the specimen having been sectioned to show the spinal canal.

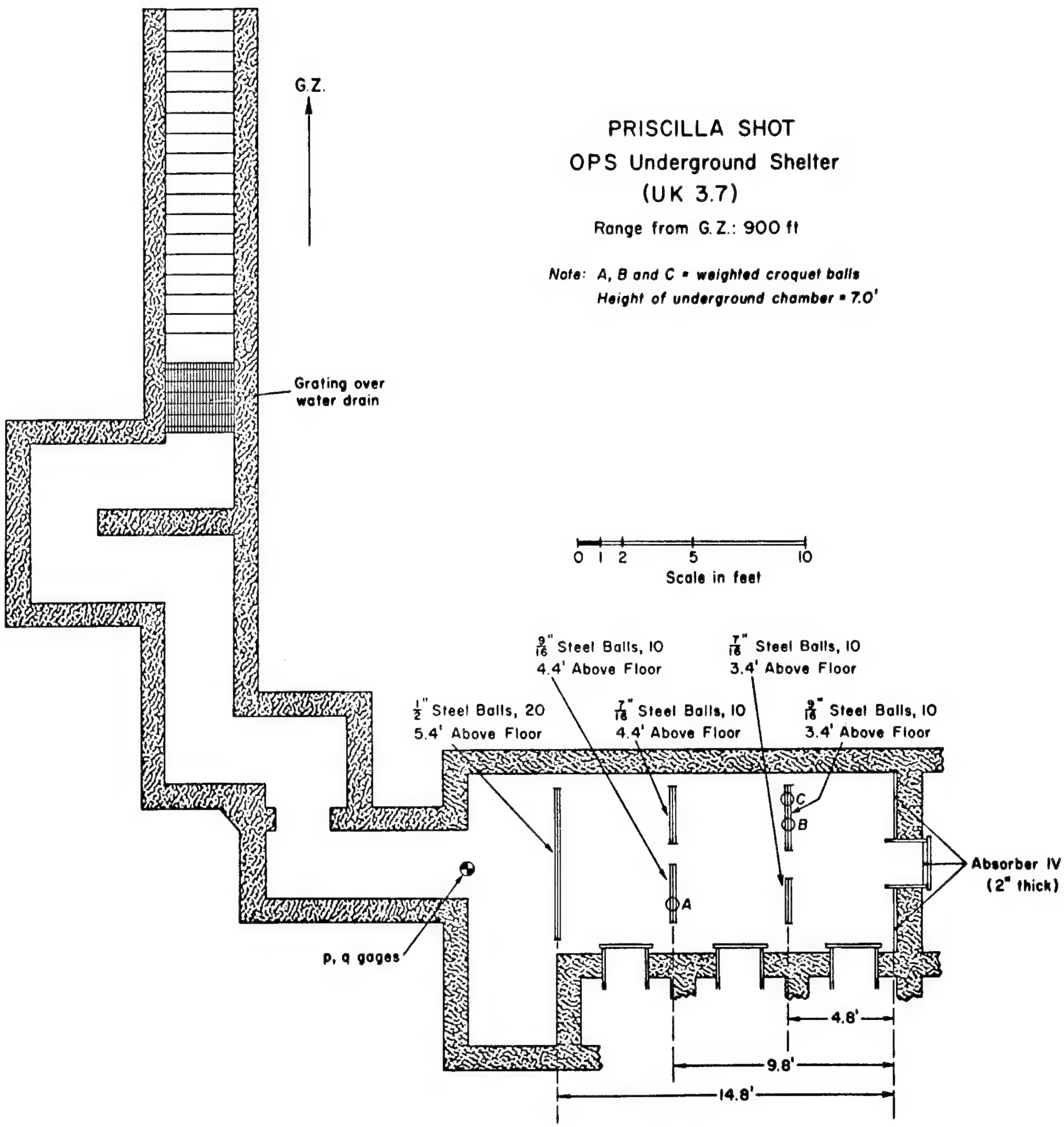
Animal G-1 in Shelter 8002 was translated from his original position, but apparently uninjured from impact even though his harness was partly torn probably by force against a heavy restraining line used to avoid escape of translated animals postshot.

2. <u>Translational Studies (1957 – UK-3.7 Structure)</u>

In one event in the 1957 test series, a translational study[21] was done inside the old 3.7-UK Shelter, a cross section of which is shown in Figure 32. As can be seen, the somewhat tortuous entryway faced ground zero and led into the main room of the structure through a short hallway facing the far wall about 18 ft away. A missile absorber (Grade IV Styrofoam), cemented to the end wall, aided an attempt to determine velocities of weighted croquet balls and steel spheres (1/2 in. and 9/16 in. in diameter), suspended from the ceiling at various distances from the wall. One of the croquet balls and 8 of the spheres held in aluminum-foil envelopes as shown in Figure 33 and torn from their fragile containers by the blast winds, made identifiable impact marks in the absorber. The test objects, having acceleration coefficients that are close to those for "randomized man," gained velocities that were 45 ft per second (31 mph) for the croquet ball, and on the average were 53 ft per second (36 mph) for the 9/16 in. spheres and 129 ft per second (88 mph) for the 1/2 in. steel balls.

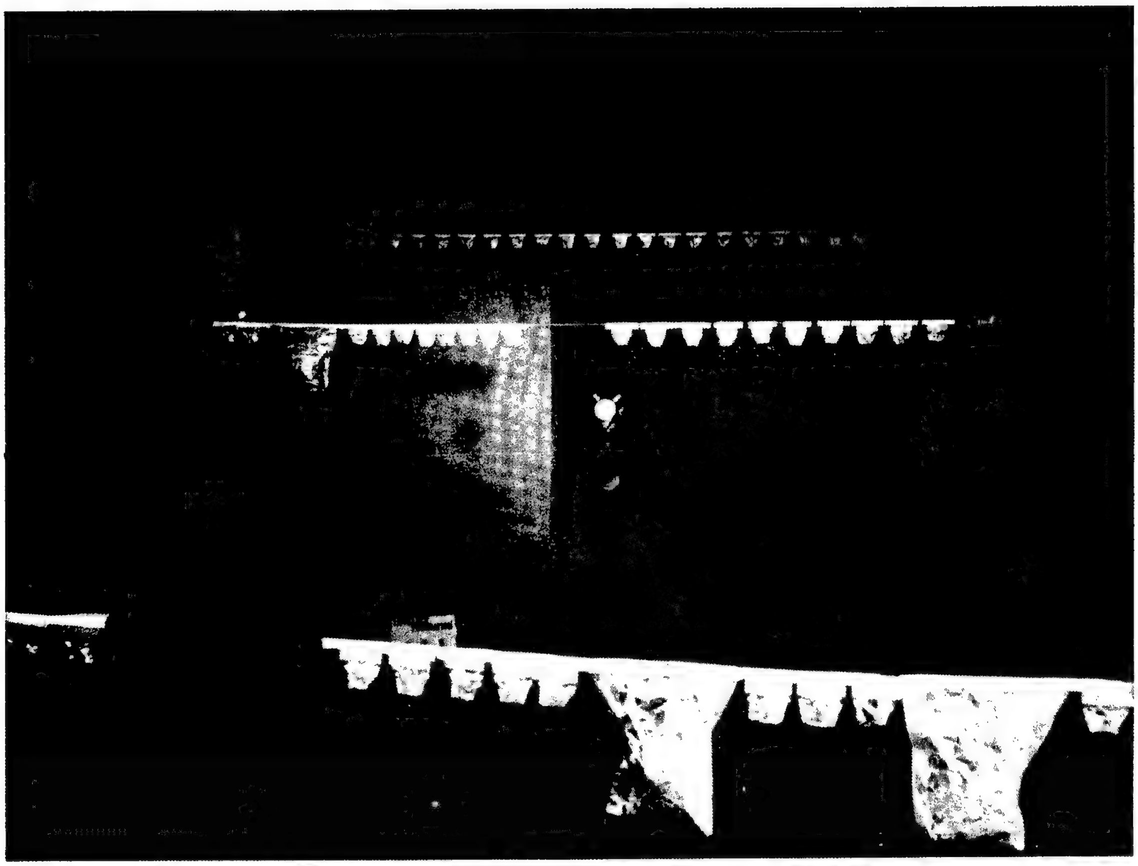
Fractured lumbar vertebra of dog K-1[5]

Figure 31



Station OPS layout chart.[21]

Figure 32



Station OPS, preshot, showing spheres and three croquet balls in foil bags. Photograph was taken near the absorbing material looking toward the entrance.[21]

Figure 33

These figures and the range of velocities noted are summarized in Table 20. It is noteworthy that one of the 1/2 in. spheres was traveling 159 ft per second (108 mph) when it hit the wall 14.8 ft away.

Several other observations concerning the shelter translation study are worthy of mention. First, the identifiable impact points of the spheres used in the experiment were mostly located in the upper right-hand quadrant of the absorber suggesting that the winds had a swirling motion after they entered and filled the shelter.

Second, also retrieved from the absorber were 69 missiles apparently formed from molten metal. These were hot on impact, judging by the appearance of the Styrofoam, and their impact velocities could not be determined; i. e., penetration was enhanced by melting the absorber. The origin of these metal missiles, fairly spherical in shape and weighing from 1 to 71 mg, is not known for certain. They may have originated from the floor, being metal beads from welding operations. However, this seems unlikely because the preshot photographs of the shelter indicate that the floor had been swept reasonably clean. The metal objects may have entered the shelter from outside, but from where is "anyone's guess."

Third, 194 stone-like missiles were also recovered from the absorber at the end of the 3.7 Shelter. Some appeared to be concrete chips; others looked like "natural" stones. Impact velocities for stones of 10 mg or more were determined. These ranged from 164 to 755 ft per second, the smaller stones tending to have higher velocities. Since these objects were easily going fast enough to produce serious penetrating wounds to a biologic target, as will be noted subsequently, the velocity-mass relationship is included here as Figure 34. Also the spatial distribution of the missile is shown in Figures 35 and 36 in terms of missiles per square ft, their mass in mg, and their velocities in ft per second, plotted over a height-width diagram representing the end wall of the Shelter (called Station OPS in Reference 21).

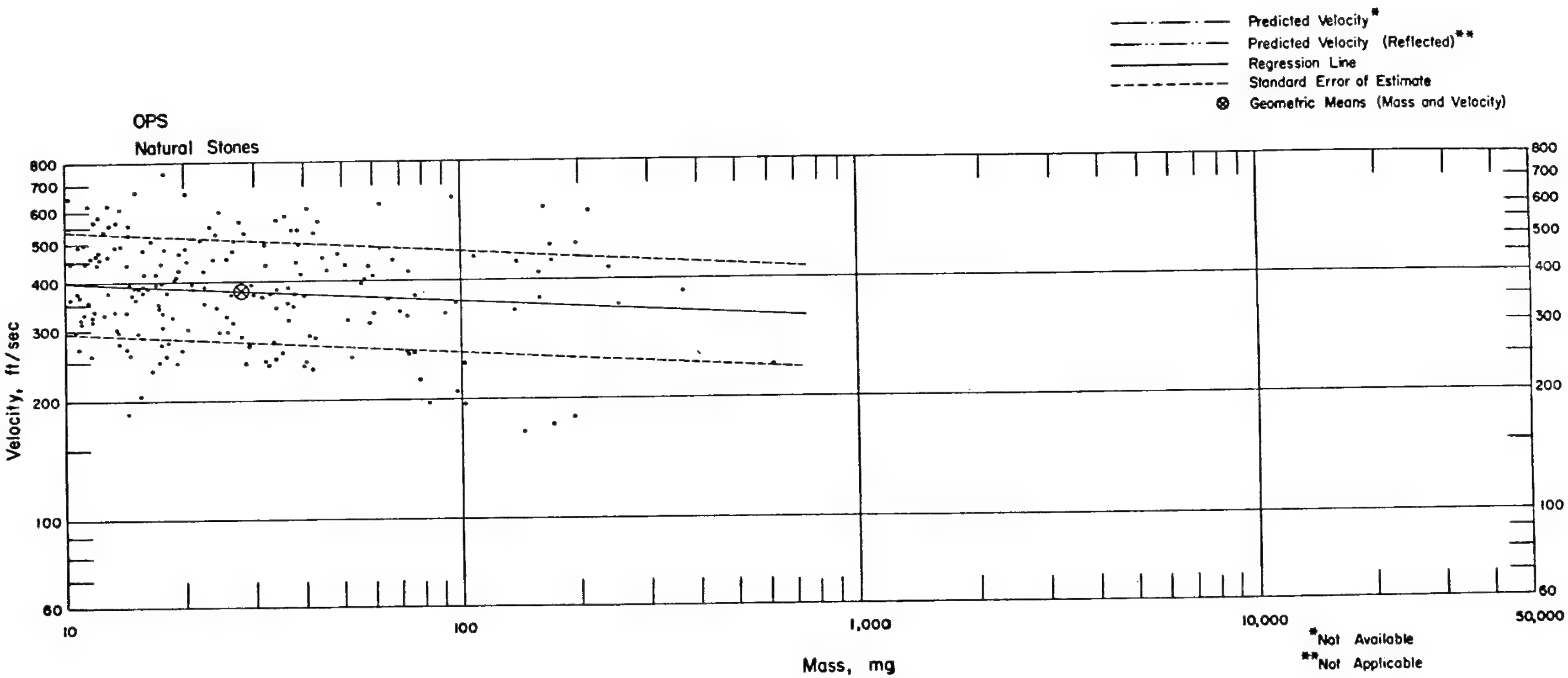
As with the metal missiles mentioned above, the origin of the "natural" stone missiles cannot be stated with certainty. If they did not come from outside, they may have arisen from the concrete

TABLE 20

SUMMARY OF TRANSLATIONAL DATA FOR SPHERES EXPOSED IN UK 3.7 SHELTER[21]

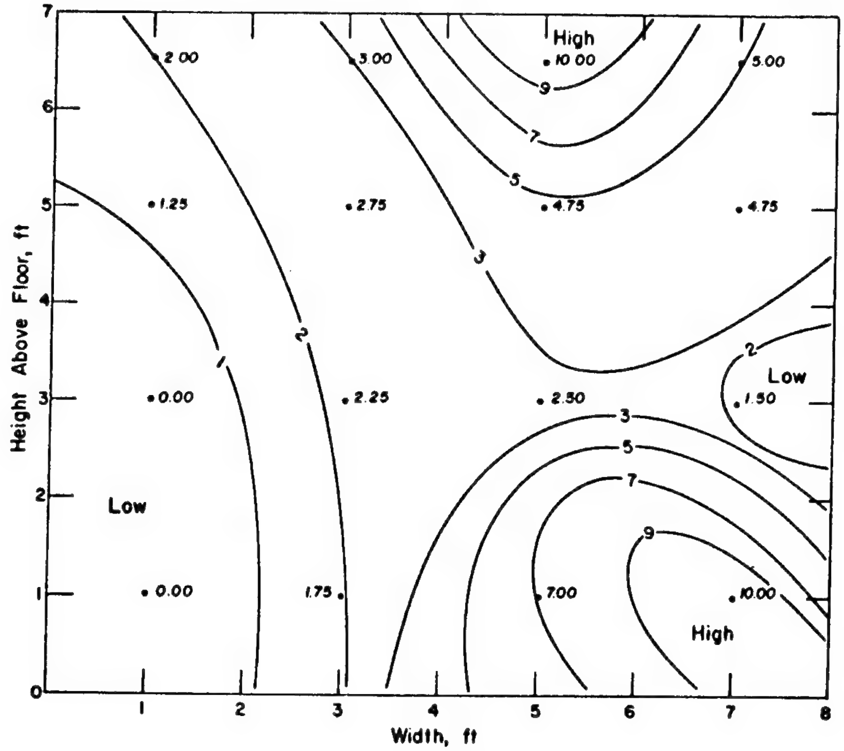
Sphere Type and Diameter	Acceleration Coefficient (a) ft^2/lb*	Distance to Absorber ft	Number Missile Analyzed	Velocity ft/sec					
				Average		Minimum		Maximum	
				ft/sec	mph	ft/sec	mph	ft/sec	mph
1/2" Steel	0.0348	14.8	6	129	88.0	99.1	67.6	159	108
9/16" Steel	0.0310	9.8	2	52.9	36.1	52.6	35.9	53.2	36.3
Croquet ball	0.0350	9.8	1	45.0	30.7	--		--	

*The acceleration coefficient, $a = A/M \cdot C_d$
A = area; M = mass; C_d = drag coefficient

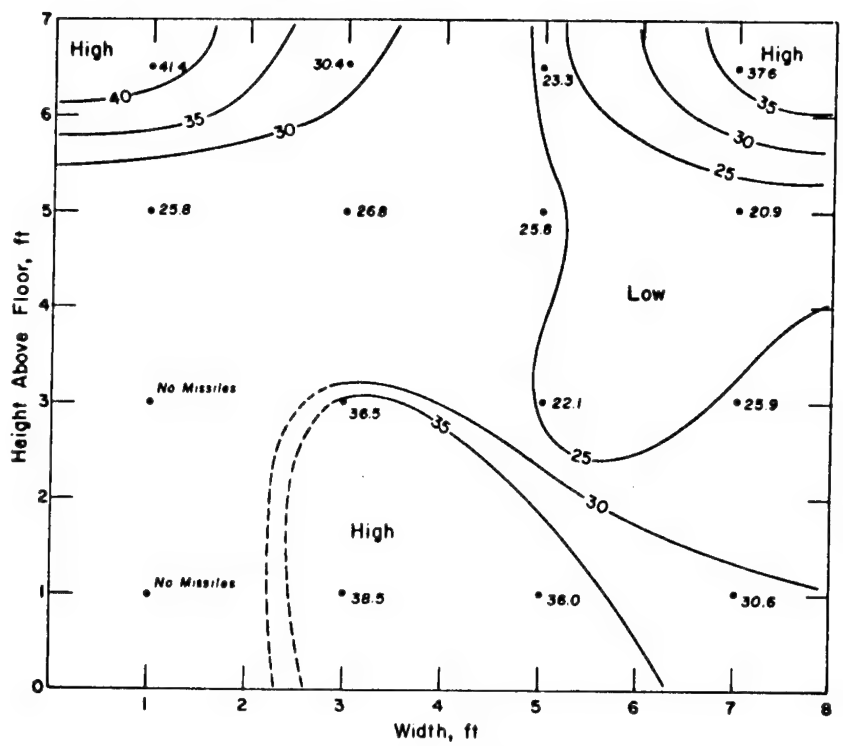


Analysis of natural-stone missiles from station OPS: $n = 194$; $\log v = 2.6493 - 0.0506 \log m$; $E_{gv} = 1.35$; $M_{50} = 28.8$ mg; $V_{50} = 376$ ft/sec.[21]

Figure 34

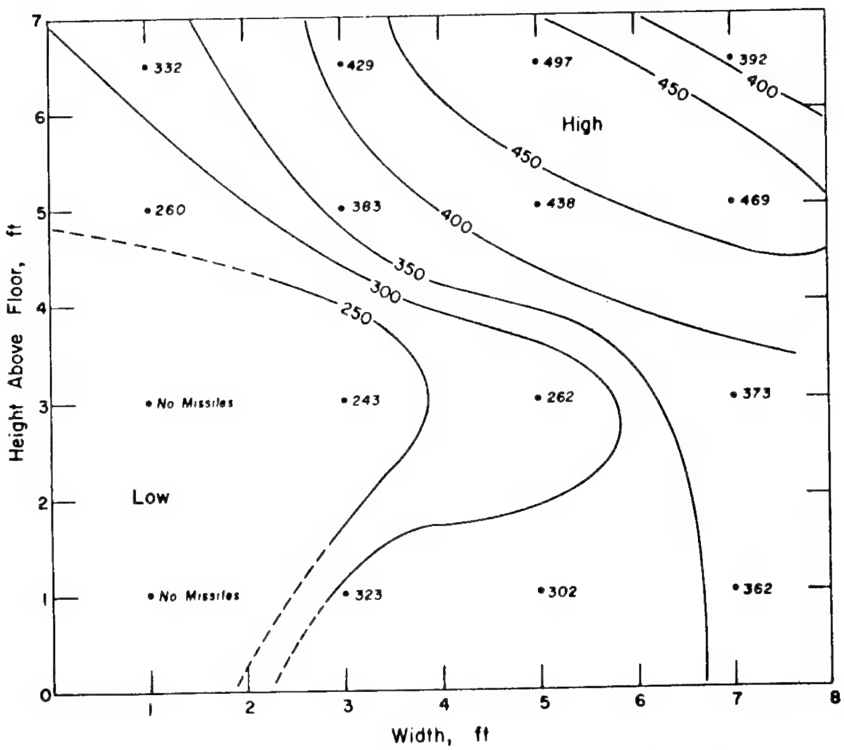


Spatial distribution of natural-stone missiles recovered from station OPS. Numbers indicate missiles per square foot. 21



Spatial distribution of the average masses (in mg) of natural-stone missiles recovered from station OPS. The average mass of missiles caught within a particular area segment was plotted at the center of the segment. 21

Figure 35



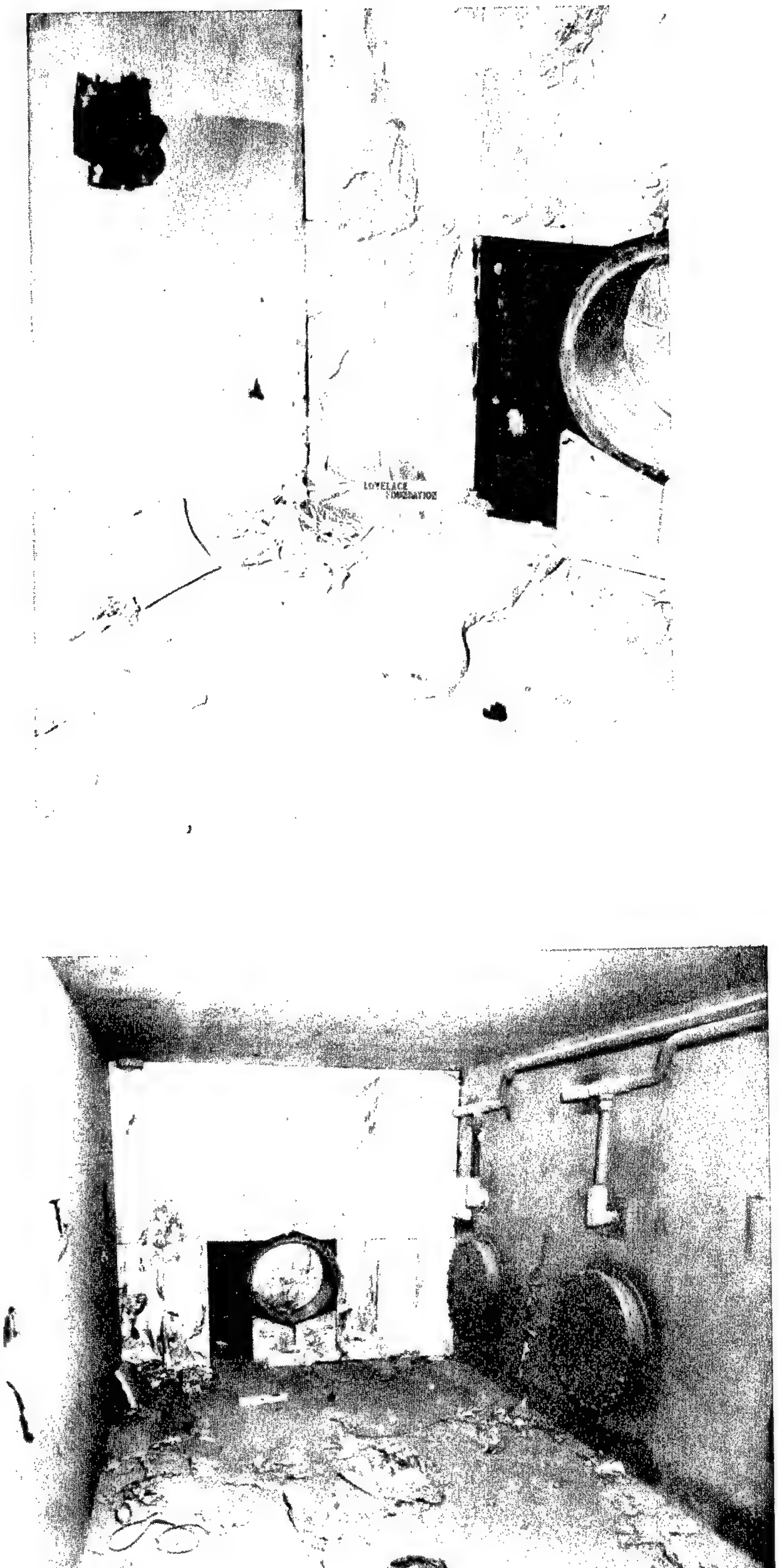
Spatial distribution of the average velocities (in ft/sec) of natural-stone missiles recovered from station OPS. The average velocity of missiles caught within a particular area segment was plotted at the center of the segment.[21]

Figure 36

baffle and/or other portions of the entryway that were cracked, chipped and scoured by the blast winds. In any case and without question whatsoever, they represented an indubitable hazard had the shelter been occupied.

Fourth, the postshot photos of the shelter, two of which are reproduced as Figure 37, showed the interior to be littered with test debris with dirt all over the place. A piece of the missile absorber was torn from the end wall, as was a square, test piece of Styrofoam III, which preshot was cemented to the left wall (see black area due to cement in the lower photograph of Figure 37). The Styrofoam III slab, though covered with aluminum foil when exposed, was "singed" on the edges, showed signs of heat distortion and was compressed, an event not observed with the denser and stronger Styrofoam IV employed as absorber on the end wall of the structure.

Fifth and finally, the 3.7 Structure survived the blast without collapsing even though the outside maximum pressure was close to 65 psi, but as an open shelter, would hardly have been a place for anyone but the most carefully prepared and protected occupants. Unfortunately the "Q" and pressure gauges inside the shelter did not function, but conditions of biological significance can be inferred from data already given for the animal work carried out in the 1955 and 1957 group shelters mentioned above.



Postshot view of the UK-3.7 Structure

Figure 37

C. Ground Shock (Secondary, Tertiary and Some Miscellaneous Effects)

The response of surface or subsurface shelters exposed to blast-induced ground shock and pressures may, among other things, include gross movements of the entire structure, relatively independent motion of the component parts of the shelter, or some combinations of the two.

1. Gross Motions

The gross "en masse" motions may be downward, upward, lateral, radial or oscillating in nature. The initial direction of motion no doubt is sensitive to burst conditions and apparently can be either up or down with lateral and radial components superimposed.

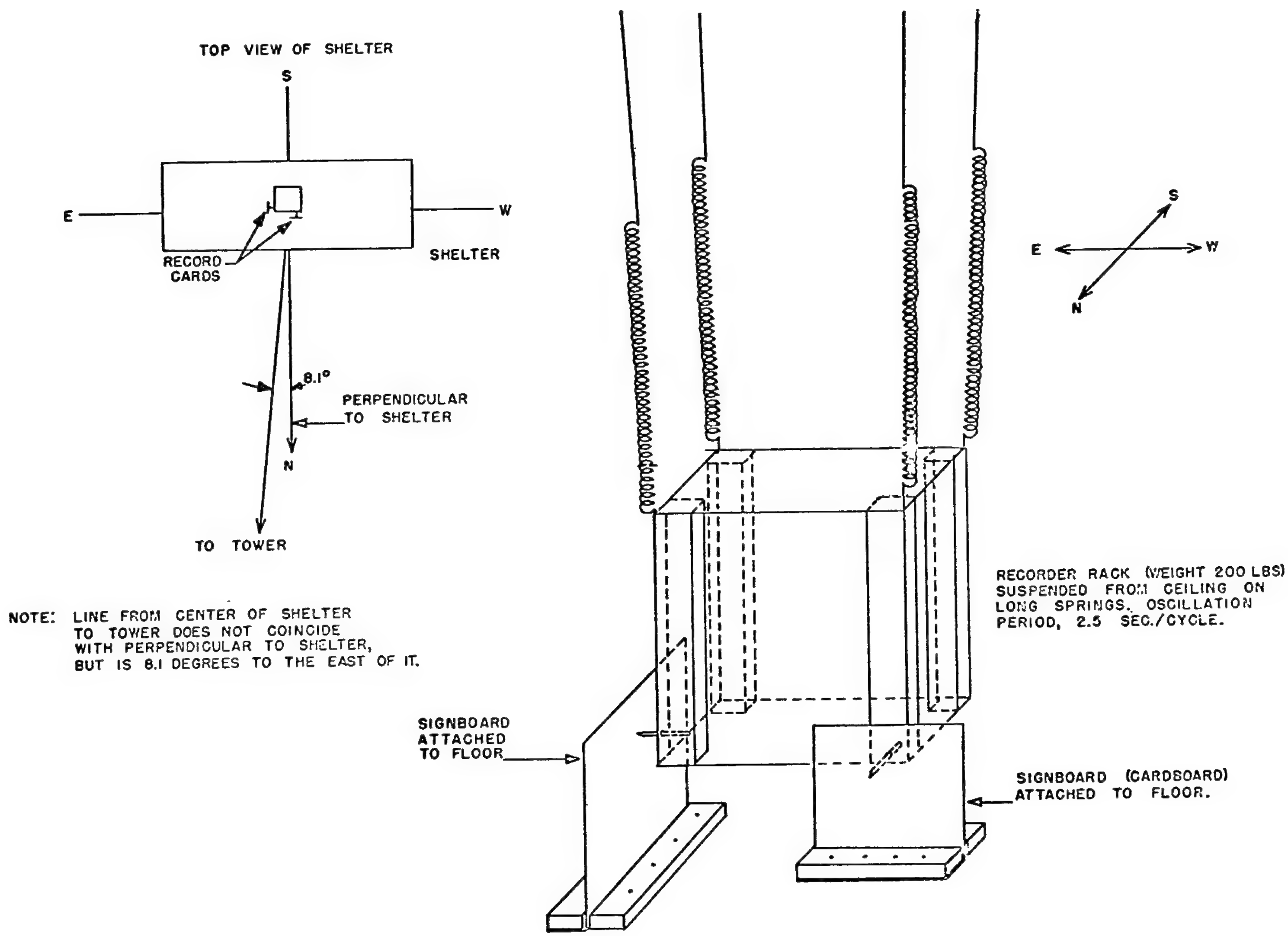
a. Air Bursts

For example, in 1955 the initial gross motion of a group shelter, generally similar to that depicted in Figure 15 except for the absence of a partition and the presence of doors that were closed during the test, was recorded.[22] The shelter was located at a range of 1,050 ft beside the Series II group shelter discussed previously.

The 1955 Group Shelter (34.3)

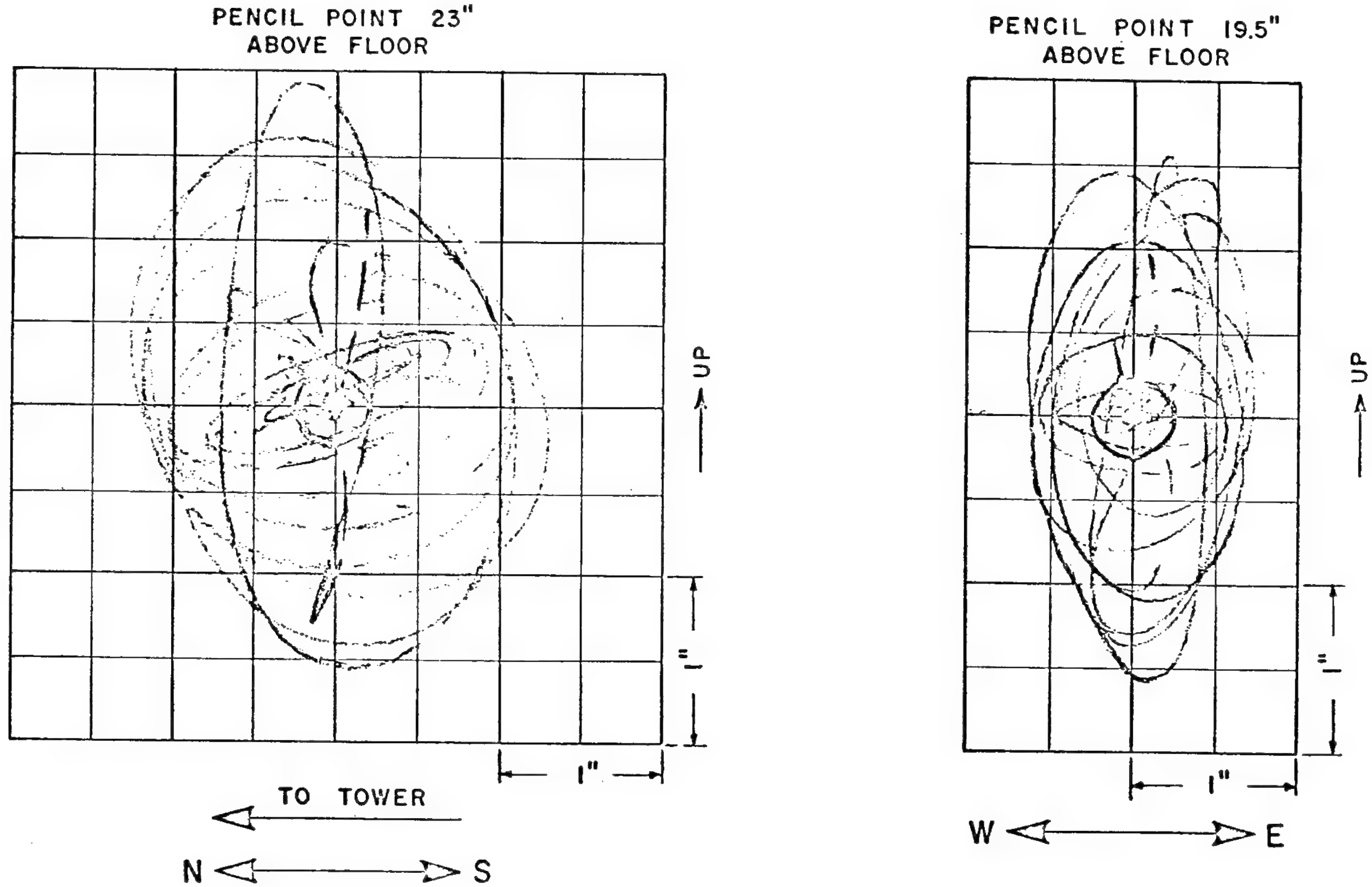
Figure 38 shows the displacement gauge designed to record the initial motion of the structure.[22] The box in the figure, to which two pencils were attached, supported four electrocardiographic recorders and related gear, weighed 200 lbs, and was suspended from the ceiling of the structure with springs (a shock-protective scheme).

Figure 39 is a reproduction of the tracings obtained.[22] The dotted portions of the records, apparently caused by the vibration of record cards against the pencils, represent the initial movement of the shelter. One of the records shows a 1.25-in. downward initial motion as an upward line on the trace, the floor moving away from the 200-lb box which remained, at first at least, relatively stationary.



Displacement gauge diagram[22]

Figure 38



Displacement gauge records[22]

Figure 39

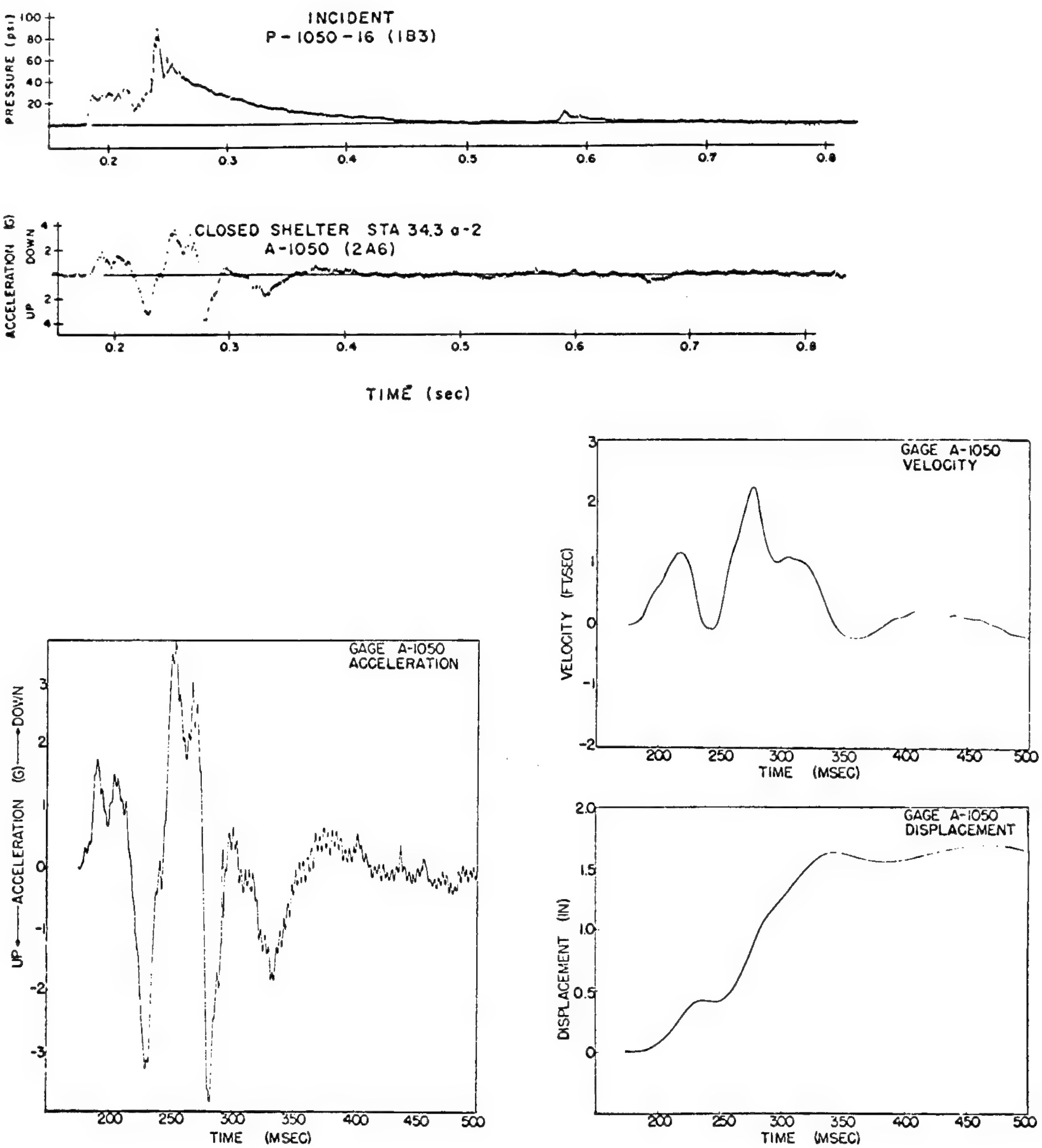
The records also indicated that the motions of the shelter had longitudinal and lateral components, but these were minimal compared with the main downward movement of the structure.

It is possible, using other data shown in Figure 40 that included the recording of an accelerometer time trace in the same structure along with subsequent integration of the trace to obtain velocity-time and displacement-time information,[8] to say several things. First, the data, indicating that the initial movement of the structure was about 1.6 in. downward, are in reasonable agreement with those from the displacement gauge noted above and shown in Figure 39.

Second, the changes in the acceleration record and the velocity and displacement data derived therefrom, as presented on the lower three records of Figure 40, indicate that the downward movement of the group shelter occurred in two phases, the second greater than the first (see lower right-hand trace in Figure 40).

Third, a comparison of the incident pressure-time record with the acceleration-time record, both shown at the top of Figure 40, indicates that the initial acceleration response of the structure corresponded in time with the arrival of the early portion of the overpressure. Also the first and second displacement phases of the shelter were associated in time with the arrival of the early and the late increases in overpressure. Too, there was a correspondence between the magnitudes of the early and the late arriving overpressures — the latter being larger — and the first and greater second phase of the displacement, respectively.

These facts along with further contemplation of Figures 39 and 40 establish or suggest four conclusions: namely, first, that for certain kinds of soil at least the disturbance in the ground induced by the air shock wave is associated with significant gross motions of a subsurface structure; second, that under conditions of more "spring" in the soil, the motion may be more strongly oscillating and perhaps faster in response (up and down and not just down as was the case with the group shelter noted); third, that the main portion of



Pressure, acceleration, velocity and displacement-time records for an underground group shelter exposed in 1955 at a range of 1050 ft from a 29-kt detonation on a 500-ft tower.[8]

Figure 40

the gross early movement of a structure will be downward and fourth that lateral and radial motions depending on orientation of the shelter may be significant components of gross motion of the structure.

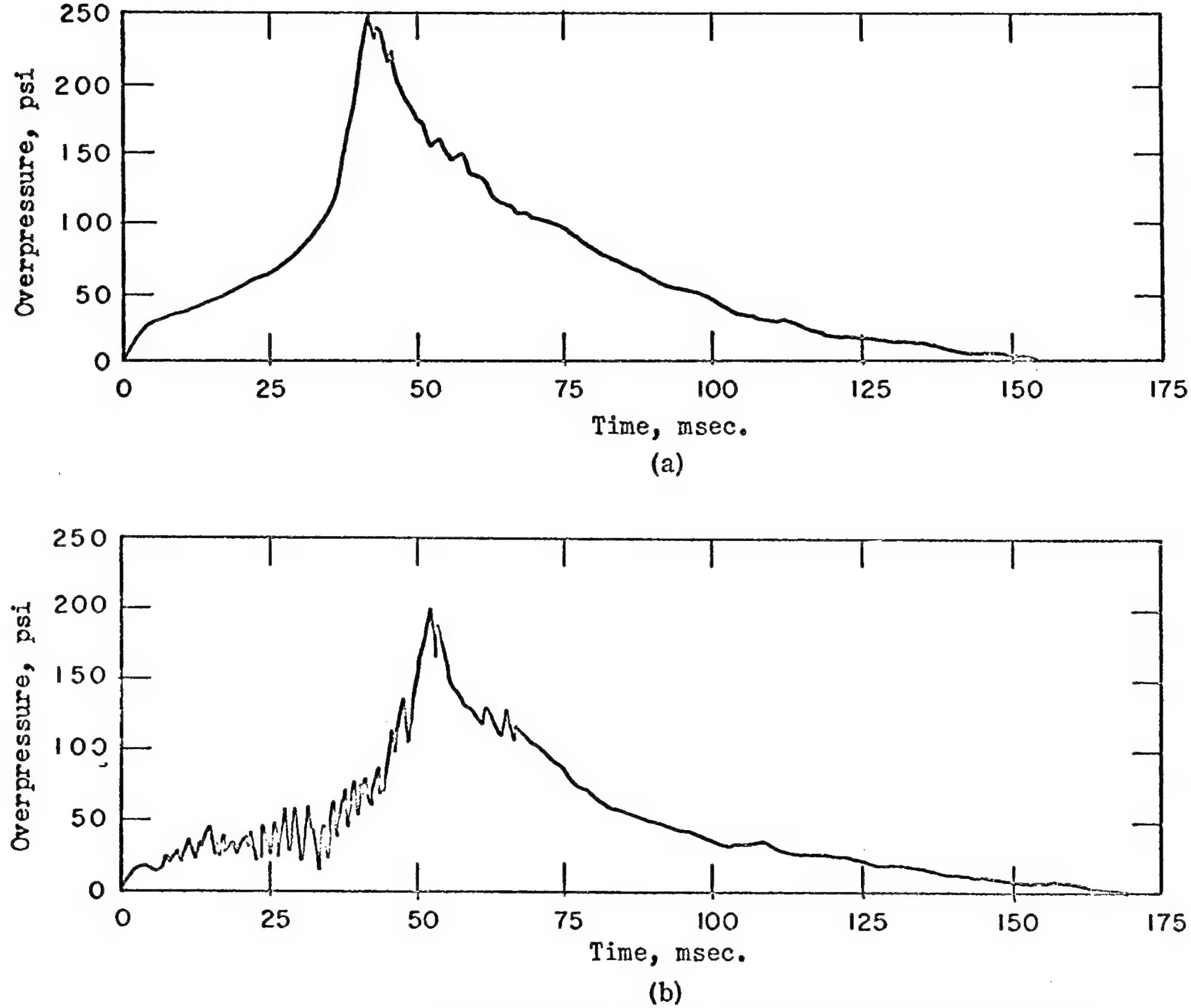
The 1957 Corrugated-Metal Pipe Structures

In 1955, two 10-gauge, corrugated metal, structural-plate shelters, 7 ft in diameter with timbered ends, were buried at a range of 825 and 900 ft under 10 ft of compacted soil, instrumented and subjected to overpressure from a detonation on a 700-ft tower.[10] The free-field maximum overpressures at the shelter stations were 245 and 190 psi at the near and farther ranges, respectively. The wave forms are shown in Figure 41.

Acceleration-time records from the forward structure and the velocity and displacement-time curves obtained by integration[10] are shown in Figures 42, 43 and 44. Although, as with the 1955 group shelter, the motion of the 1957 cylindrical shelter was mostly downward with some lateral movement, there was importantly also an initial upward component of acceleration and velocity as can be seen from the records. Though postshot tests indicated the accelerometer was underdamped,[10] and one was cautioned to regard the magnitude of the G-time changes accordingly and since the transient diameter changes recorded were considered independent of the absolute displacement of the pipe, it seems clear that for an air burst, a subsurface structure can move initially upward. There may be three possible explanations for this: viz., (1) as the air shock moves across the ground, a wave moving faster in soil arrives at the shelter somewhat before the air shock does; (2) the disturbance induced in the soil at ground zero by the arrival of the incident pressure wave may emanate radially and arrive at the shelter before the disturbance associated with the passage of the air pressure wave over the shelter; or (3) some combination of (1) and (2). These factors are of course very much sensitive to range, yield, burst conditions and the character of the subsurface materials and may be very difficult to analyze satisfactorily.

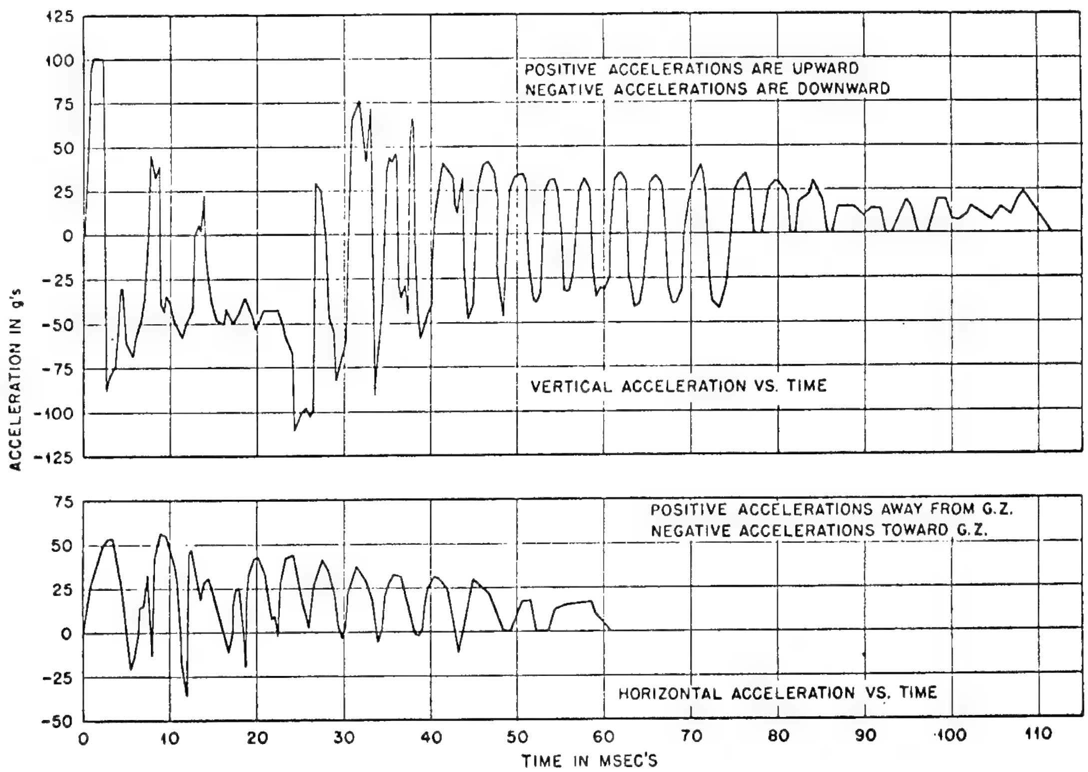
b. Subsurface Burst (Nonventing)

A nonventing, subsurface burst, inducing a seismic-like disturbance in the soil directly, no doubt will produce a combination



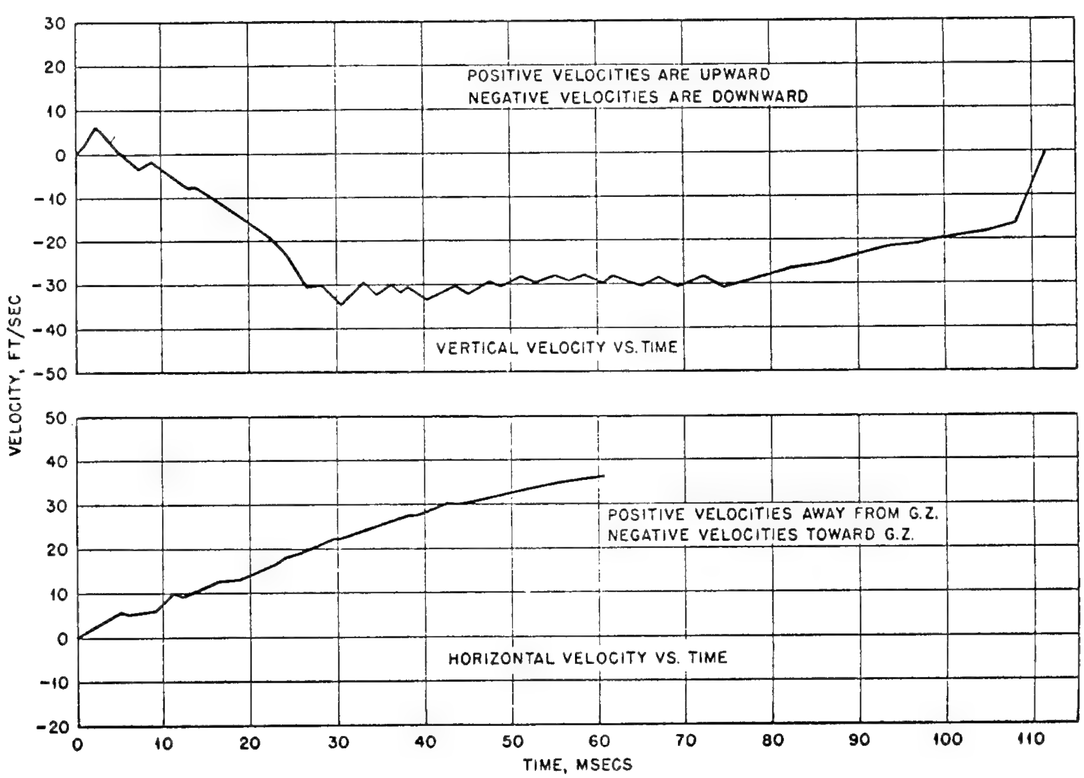
Surface overpressure-time records. (a) At 825 ft. (b) At 900 ft.[10]

Figure 41



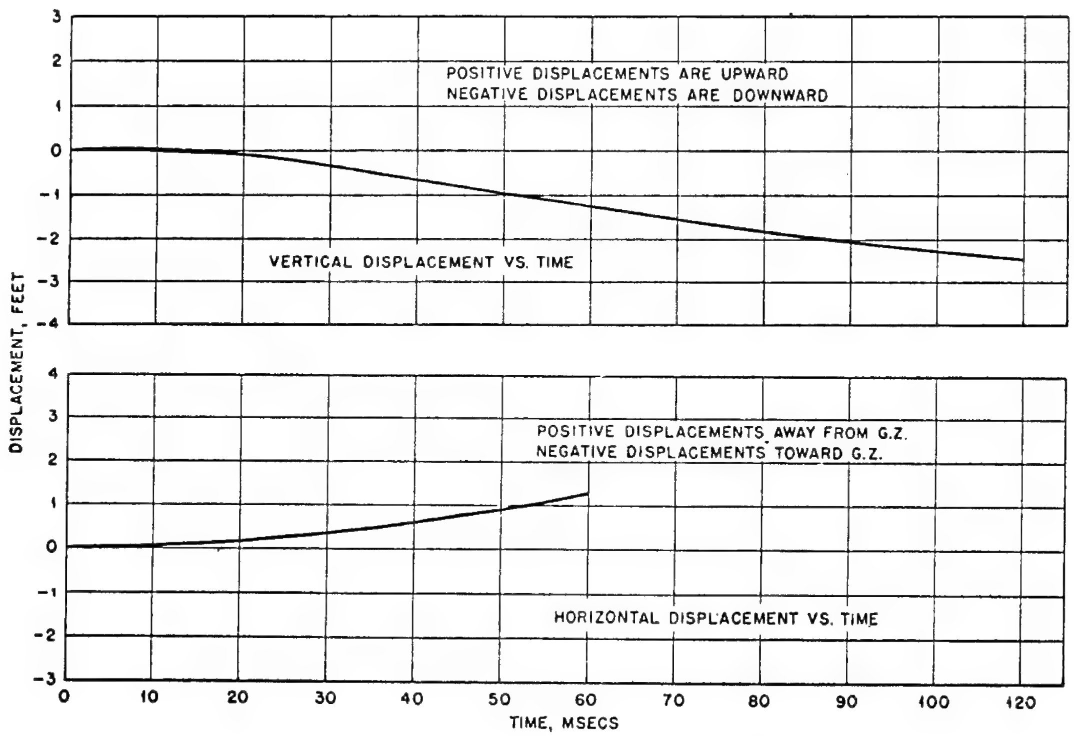
Invert accelerations, Station 1.10

Figure 42



Invert velocity, Station 1.10

Figure 43



Invert displacements, Station 1.10

Figure 44

of oscillating motions having a variety of directions in a subsurface or surface shelter. Though one might expect the initial movement of the structures to be upward, especially if the shelter were on the surface or not deeply buried, a strong lateral component is likely, particularly at greater ranges. Under some circumstances, an initial downward movement is even conceivable.

c. Surface or Subsurface Burst (Venting)

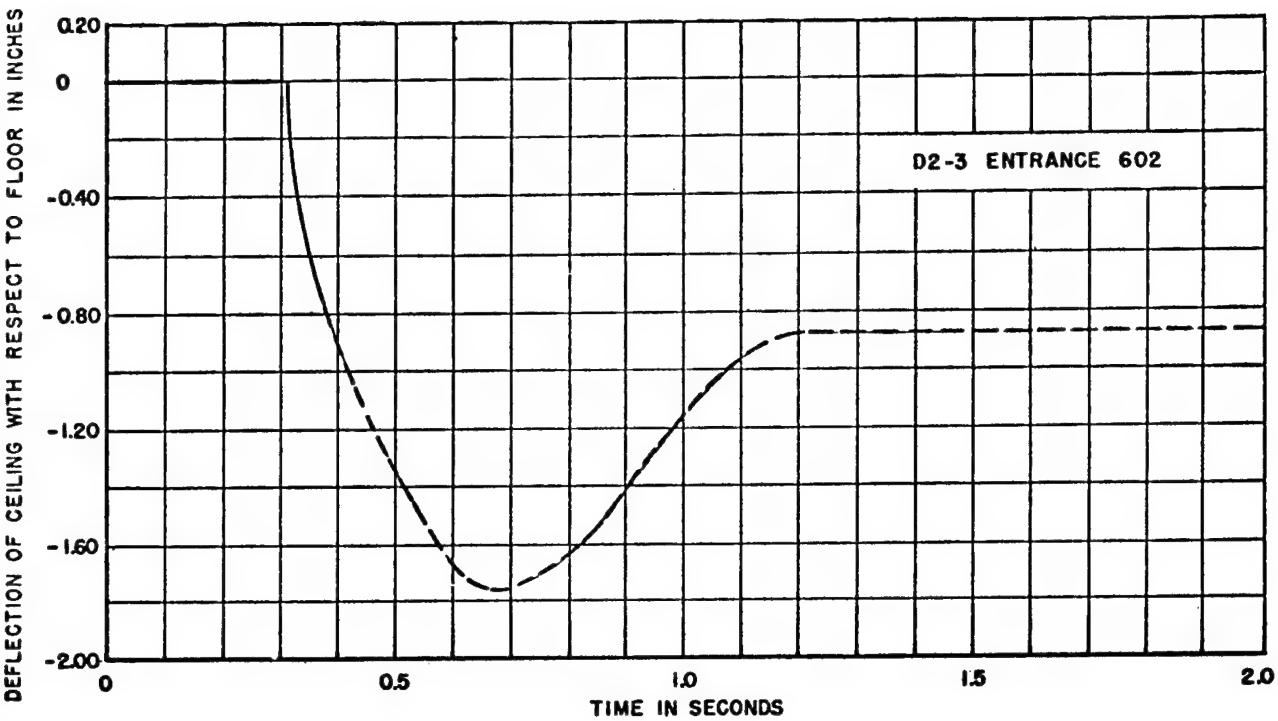
It seems reasonable to believe that a surface, or a subsurface burst that vents, will in general induce motions in a surface or subsurface structure that involve some combination of those discussed above for air and nonventing underground explosions. In all probability the direction of the initial motion of the structure will be influenced by the relative arrival times of (a) the seismic-like disturbances emanating through the soil from the explosive source and (b) the downward pressure exerted at the ground-air interface as the overpressure wave in air moves away from ground zero. Again these two factors will be sensitive to range, yield, burst conditions and the speeds of transmission of pressure and shock phenomena through air of varying temperature on the one hand and the earth on the other.

2. Component Motions

Whether or not a shelter is grossly disturbed by blast-induced ground shock, or during the period it is so disturbed, the several structural components can undergo a variety of independent motions. These may be transient, reversible, irreversible, mild, severe or involve partial or complete structural failure depending upon local conditions. A few examples will be shown to emphasize the kinds of environmental variation to be anticipated in personnel shelters.

1953 Tubular Shelters

Figure 45 shows a displacement-time record of the response of the ceiling of the 1-602 tubular shelter (see lower diagram in Figure 9) at a location 10 ft inside the main room of the shelter.[15] This portion of the structure involved was made of corrugated pipe which, as the air



Displacement phenomena, shot 1; D2-3.[15]

Figure 45

shock passed over the shelter station, moved downward almost 1.8 in. in 35 - 40 msec then upward about 0.9 in. Thus the residual deformity was near 0.9 in.

1955 Basement Exit Shelters

The two forward basement exit shelters exposed in the 1955 Series II Experiment suffered gross failure of portions of the ceiling slabs that was partly due to pressure transmitted through the earth mound over the shelters. Shown in Figure 46 is a plan view of one shelter along with a preshot photograph of the entryway with inside and outside doors open.

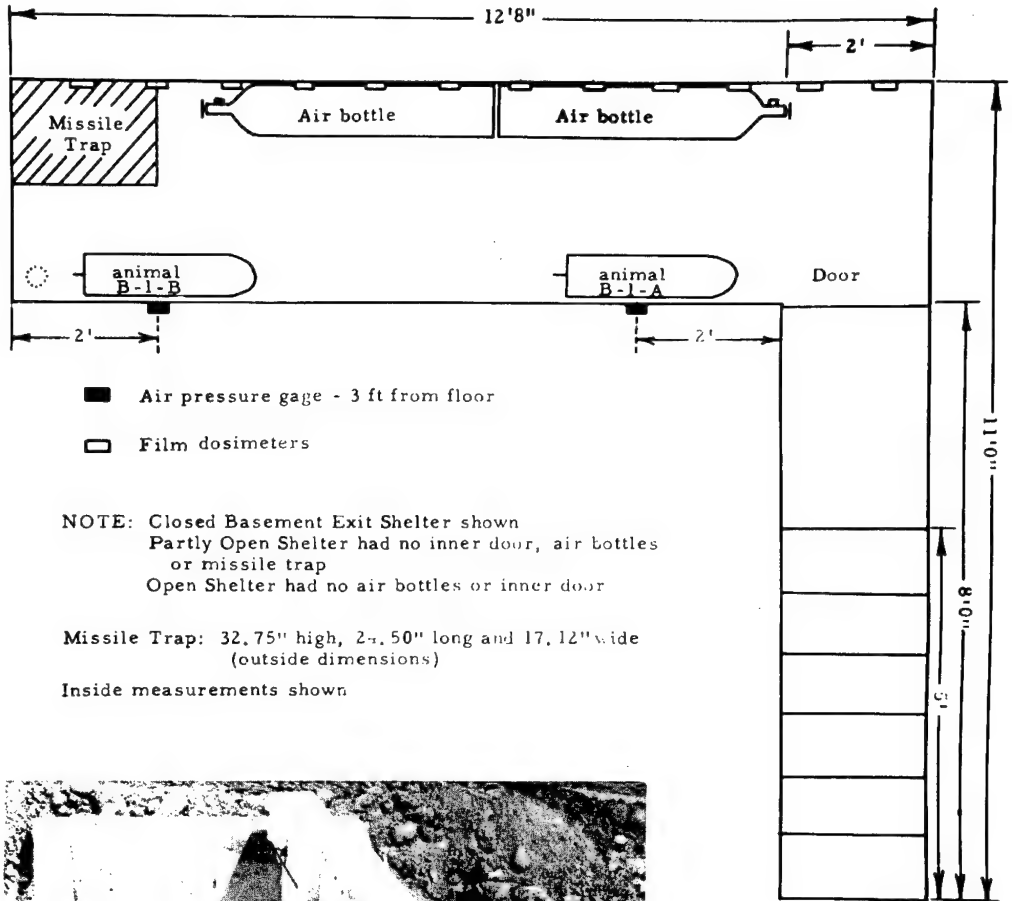
Figure 47 shows a postshot view of the BE shelter tested "closed" — note the absence of doors and the partial failure of the roof — and Figure 48 gives a postshot view looking down into the shelter tested "open." Two animals were removed from the rubble inside both shelters and the results are mentioned here mainly to emphasize that immediate biological survival does and can occur under conditions severe enough to cause gross failure of even fairly stout protective structures.

1957 Closed Shelters

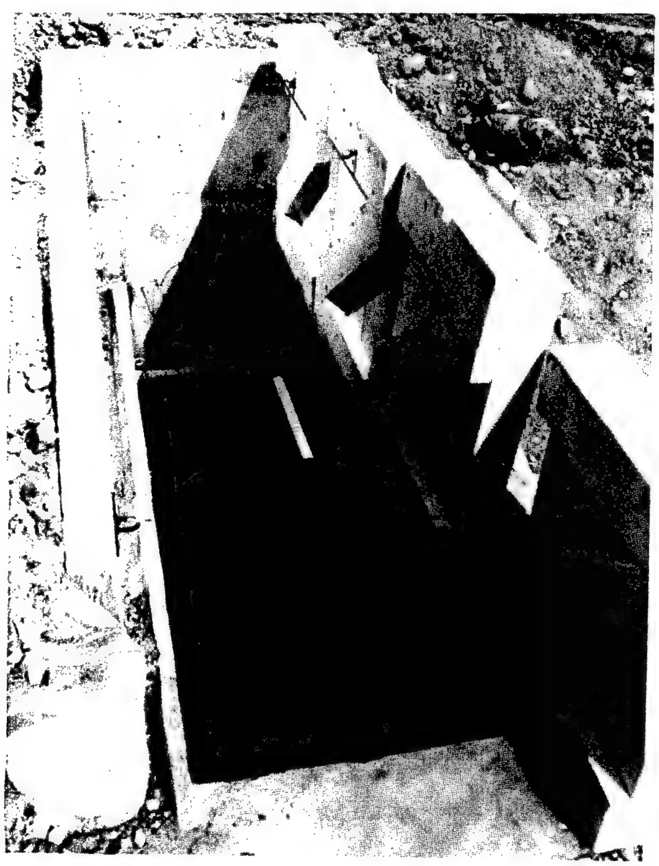
The loosening of structural materials as a result of component motion or gross spalling of concrete away from rebar or out of patched areas as shown at the top of Figure 49 can add to dust problems to be discussed later, but more importantly can, if severe, result in falling debris. Such fragments from structural failure, even if no larger than those shown in the lower portion of Figure 49 may be dangerous particularly if ceilings are high.

3. General

It is clear from what has been said that ground shock-induced motions in occupied shelters can, as is the case with high transient winds, involve translational phenomena that may or may not be hazardous depending upon the magnitude of the accelerative or decelerative forces involved. Thus, damage may well occur either as a consequence of whole-body displacement (tertiary effects) or as a result of accelerative loading from debris or from the structure itself (secondary effects).



Basement exit shelter[4]



Entryway to one of the basement exit shelters[4]

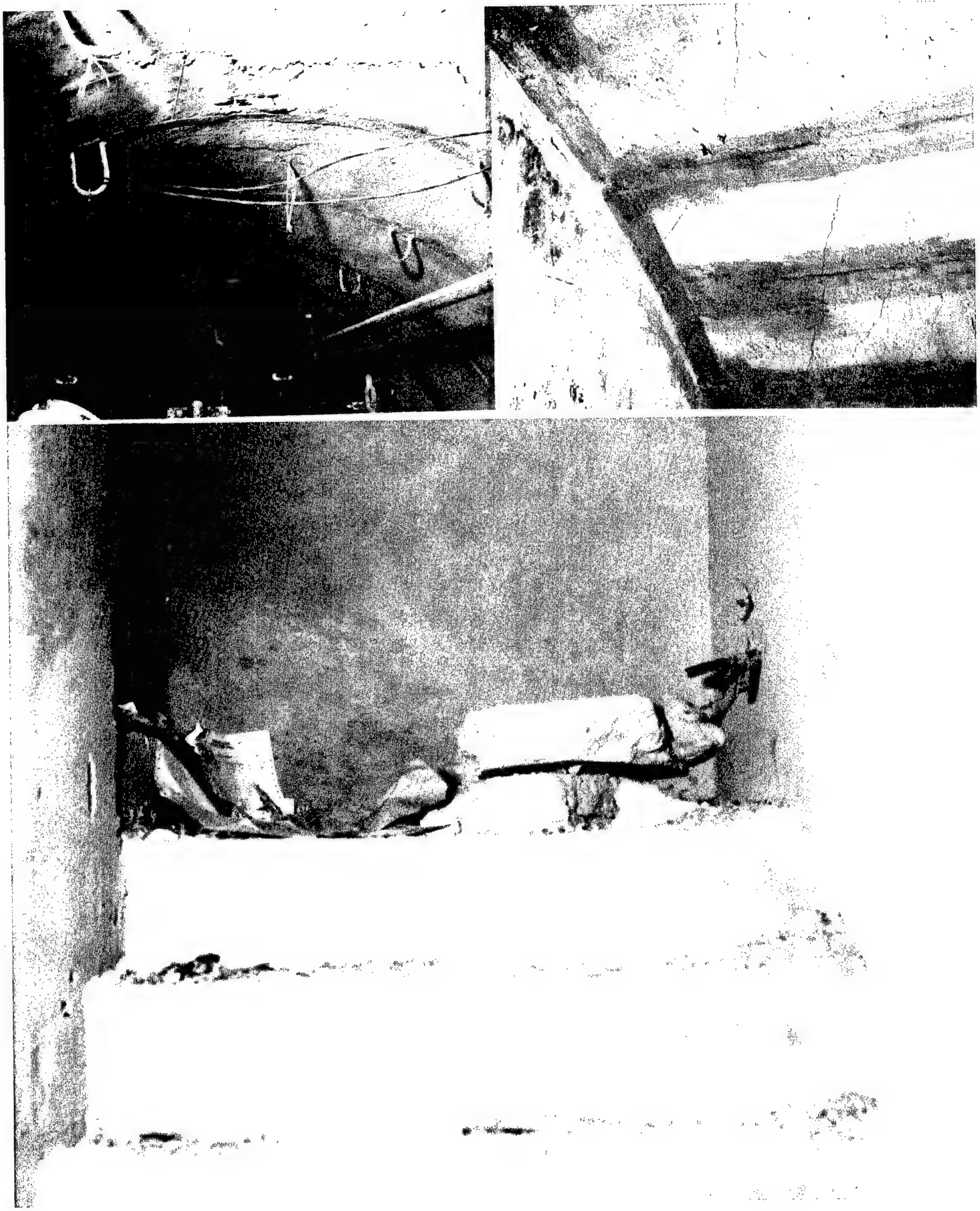
Figure 46

Forward closed basement exit shelter, postshot[4]

Figure 47

Roof damage to the forward open basement exit shelter. Note the animal between the wall and the dangling concrete slab.[4]

Figure 48



Debris and defects resulting from gross spalling and debris loosened by ground shock.

Figure 49

Finally, it needs be clear that though the initial motion of a structure may be difficult to predict, it is of considerable importance. For example, if the shelter moves up initially, the hazard may be at least threefold; viz., (1) to feet, ankles and legs, particularly if standing with knees "locked", or to any portion of the body in contact with the shelter floor; (2) to the head and neck or other areas if the individual is thrown against the ceiling; and (3) to any limb or area of the body traumatized as a result of falling. On the other hand, if the structure moves down rapidly enough initially and then the motion is reversed, occupants may face a hazard possibly worse than that of "free-fall" depending upon the relative velocities of the person and the structure when impact between the two occurs.

D. Non-Line-of-Site Thermal Problems

Temperature-time measurements were recorded inside protective structures during the 1953 and 1955 operations at the Nevada Test Site. Also a few, but significant, observations of thermal effects in experimental animals, some of a serious nature, were made during the 1953, 1955 and 1957 test series. Relevant data are summarized below.

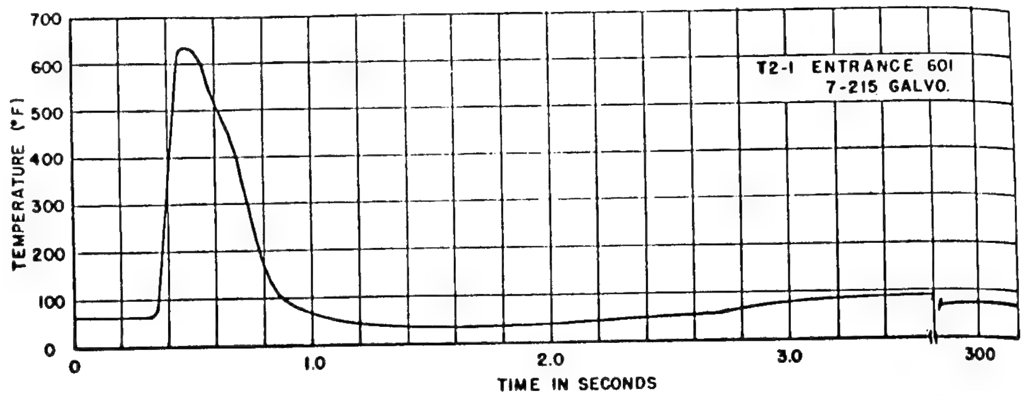
The 1953 "Open" Cylindrical Shelters

On the two experiments involving the 1953 cylindrical shelters, first described above in the section on pressure effects, temperature-time curves were recorded inside the main portions of the shelters with grid and aspirator-type thermocouples, both constructed using 40-gauge iron-constantan wire.[15]

On Experiment I, one record — shown in Figure 50 — was obtained.[15] The gauge was located on the wall of the main portion of the shelter, 14 ft from the doorway.

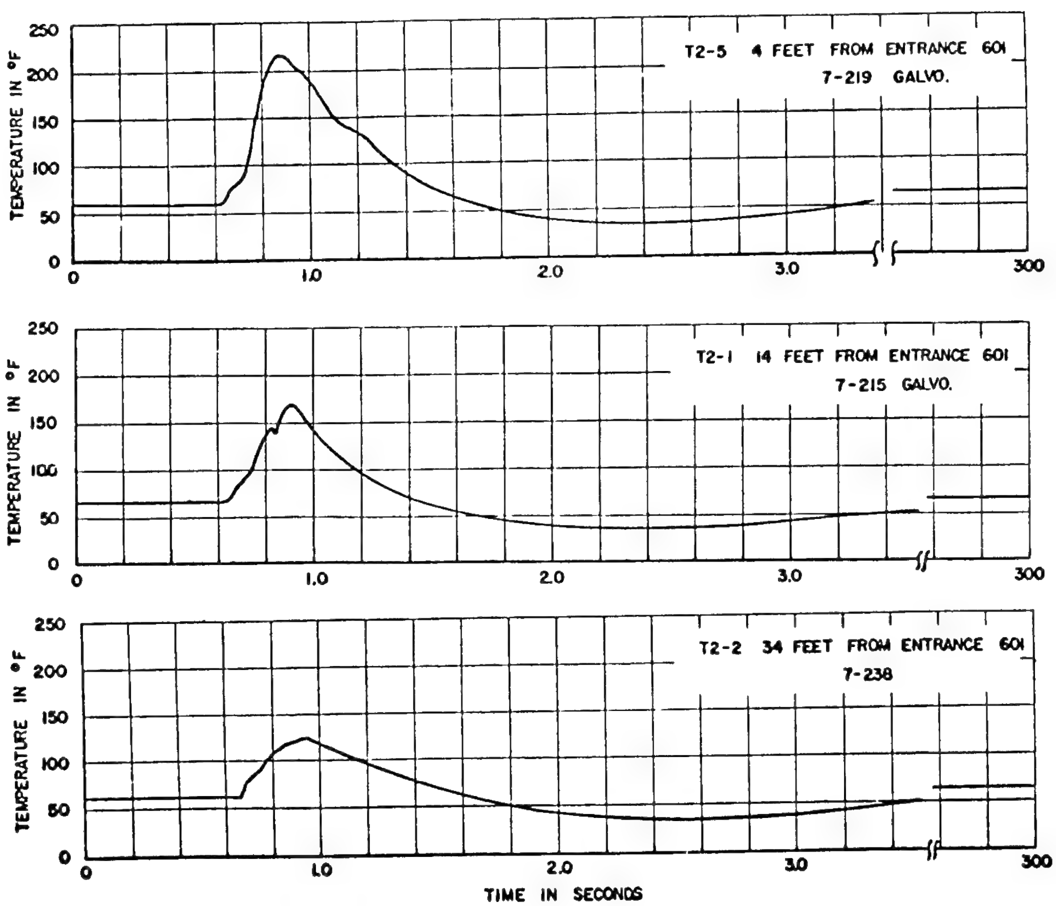
The temperature rose to about 630°F (332°C) in a few tens of msec and returned to near preshot levels in approximately 600 msec.

Samples of the temperature records obtained in Experiment II are shown in Figure 51 for the 601, and in Figure 52 for the 602, shelters.[15] The temperatures recorded on Experiment II were not so



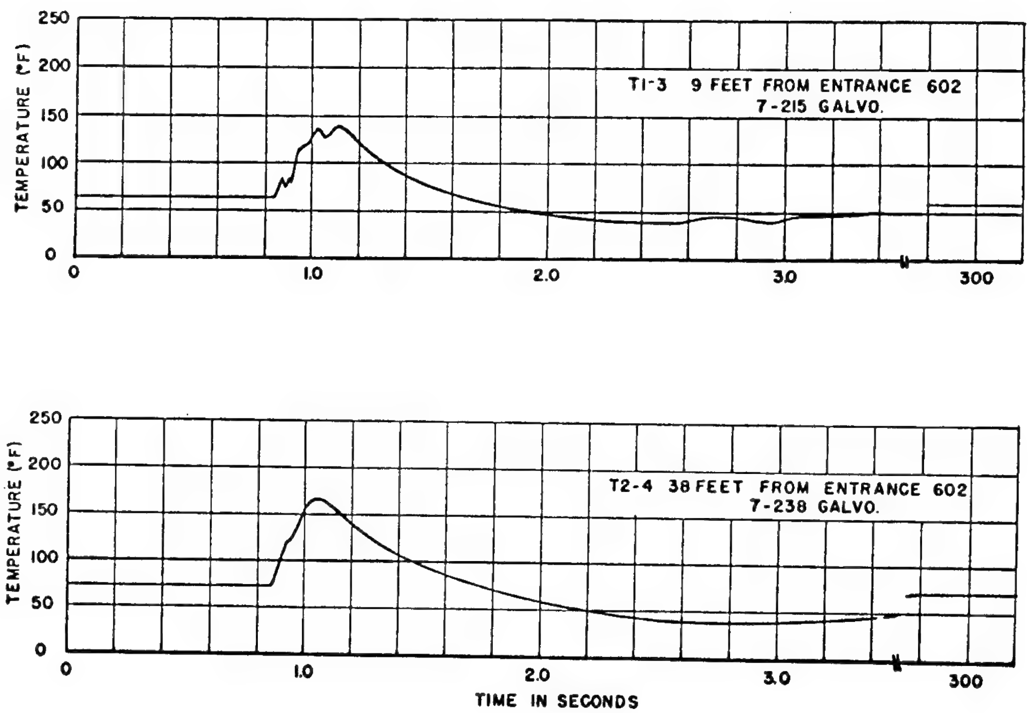
Temperature phenomena, Shelter 601, Experiment I[15]

Figure 50



Temperature phenomena, Shelter 601, Experiment II[15]

Figure 51



Temperature phenomena, Shelter 602, Experiment II[15]

Figure 52

high as the one available from Experiment I. However, the three traces included in Figure 51, taken at 4, 14 and 34 ft from the entrance of the structure, are of interest for they show a considerable decrease in temperature as distance from the entrance door is increased.

Thus, whatever was causing the temperature rise inside the shelter involved a phenomenon that appeared to be "giving up calories" as the disturbance moved into the shelter, even though the inside P_{max} did not fall much from one end of the shelter to the other. This might well mean that hot, dust-laden gases were carried into the shelter by the blast wave, an opinion expressed by Ruhl et al.[15] who pointed out that the rise in temperature recorded in Figure 50 was considerably above that accounted for by the adiabatic temperature increase expected to accompany the pressure pulse.

Regarding animals exposed in the 601 and 602 shelter studies, only 2 showed signs of thermal damage; viz., animal No. 9 at the end of the blast trap in the 601 structure on Experiment I (see upper portion of Figure 9) showed moderate singeing of the fur bilaterally, and animal No. 1 exposed in the outside ramp of Shelter 601 on Experiment II (see upper diagram of Figure 10) was slightly singed.[3]

<u>The 1953 "Sandbagged" Shelter</u>

Four other animals exhibited singeing and skin burns that could be regarded as serious during the 1953 test series.[3] These, 2 to a side, were exposed inside one end of a shelter constructed of reinforced concrete culvert, 90 in. in diameter. One end opened directly into an uncovered, walkdown ramp and the other was sandbagged closed. No temperature measurements were taken inside the shelter, which however was located at a range where about 35 psi maximum incident overpressure was recorded free field.* All

*Pressure records obtained inside the structure were not satisfactory, but indicated a P_{max} of at least 35 psi, developing at a rate of 1.15 psi per msec, occurred. All animals, on recovery, were found to have been violently displaced. They were all lethargic and stupified and 3 showed decreased response to auditory stimuli. Though 5 of 8 eardrums were ruptured and hemorrhages into the intercostal muscles and into the bladder from a mucosal tear were noted, the lungs and abdominal viscera were otherwise remarkably free of lesions.[3]

animals were burned — 3 seriously — and the fur of all was extensively singed. The location of the shelter in relation to the burst point was such that direct thermal radiation could not "shine" into the structure. It is probable the thermal effects were due to a combination of possibly thermal scatter; hot, dust-laden gases; and perhaps the adiabatic temperature rise was a contributing factor.

The 1955 Group Shelters

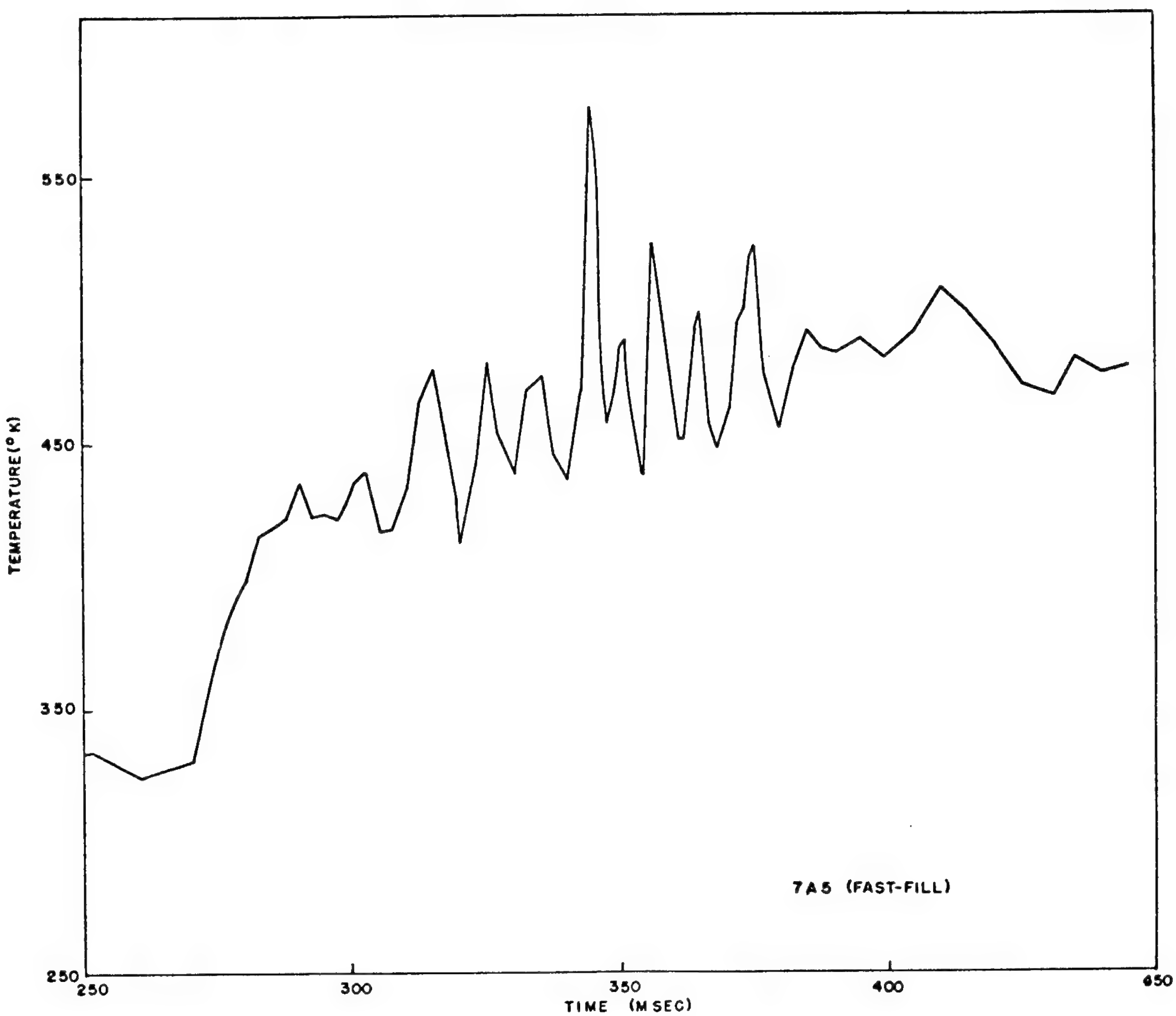
Inside the 1955 group shelters, using "whistle" gauges mounted on the walls of the structures at locations noted in Figures 15 and 18, temperature-time data were recorded by Sandia Corporation personnel.[7,8] The results are shown in Figures 53 - 56 inclusive and are summarized in Table 21.

TABLE 21

PEAK TEMPERATURES INSIDE THE "FAST"- AND "SLOW"-FILL SIDES OF THE 1955 GROUP SHELTER[7,8]

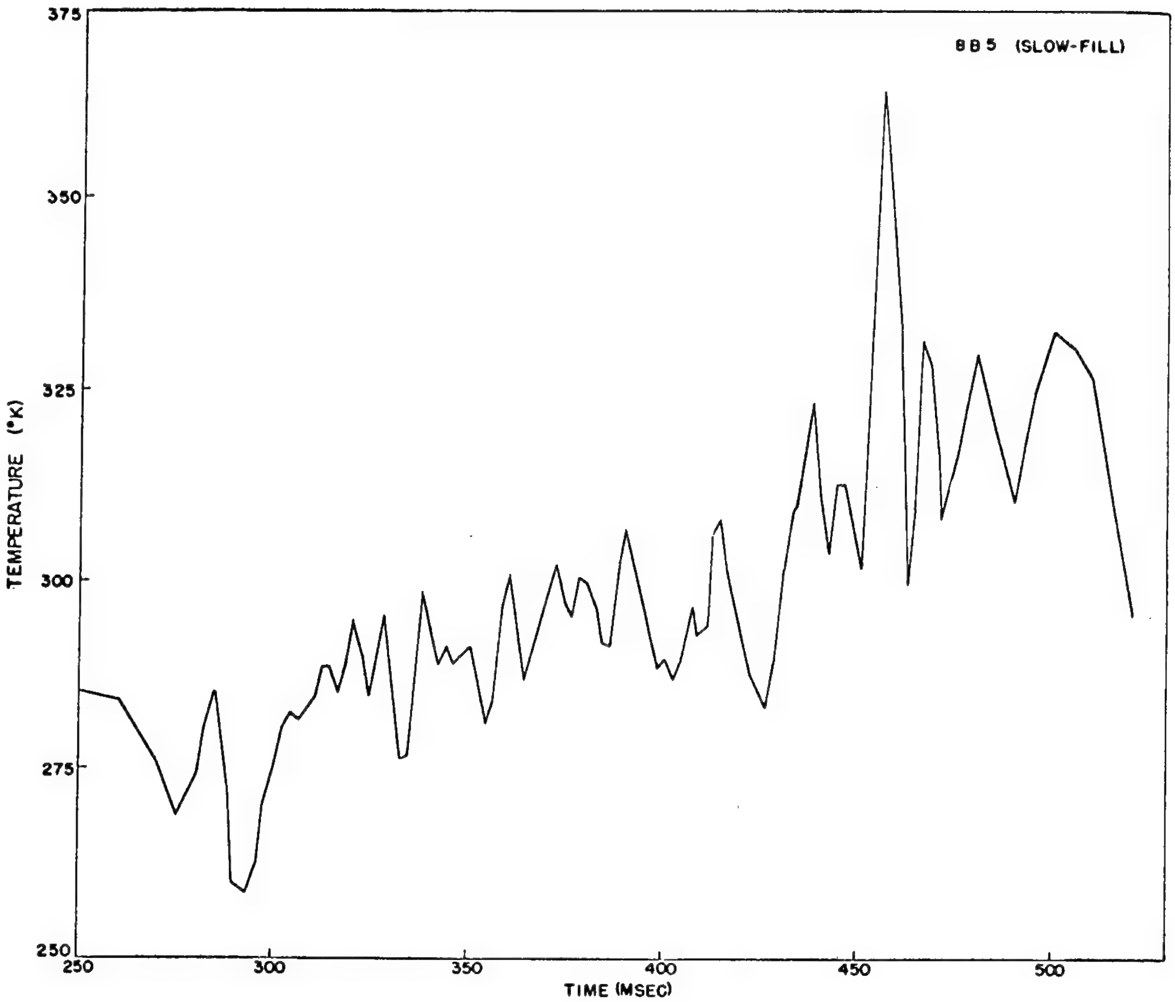
Experimental Series	Room in Shelter	Gauge No.	Peak Temperature °C
I	Fast fill	7A5	195 - 225
	Slow fill	8B5	145 - 155
II	Fast fill	1B6	215 - 225
		(early peak)	300 - 320
	Slow fill	2A2	340 - 360

The temperatures noted in Table 21 for the 1955 structures are not inconsistent with those recorded in the 1953 shelters. Also, the relationships between the occurrence of the maximum temperatures and overpressures shown in Figures 55 and 56 are compatible with the view that the influx of hot gases and dust was a significant factor contributing to the temperature rise inside the shelters. That there is about a 20-msec delay in the arrival of the temperature compared with



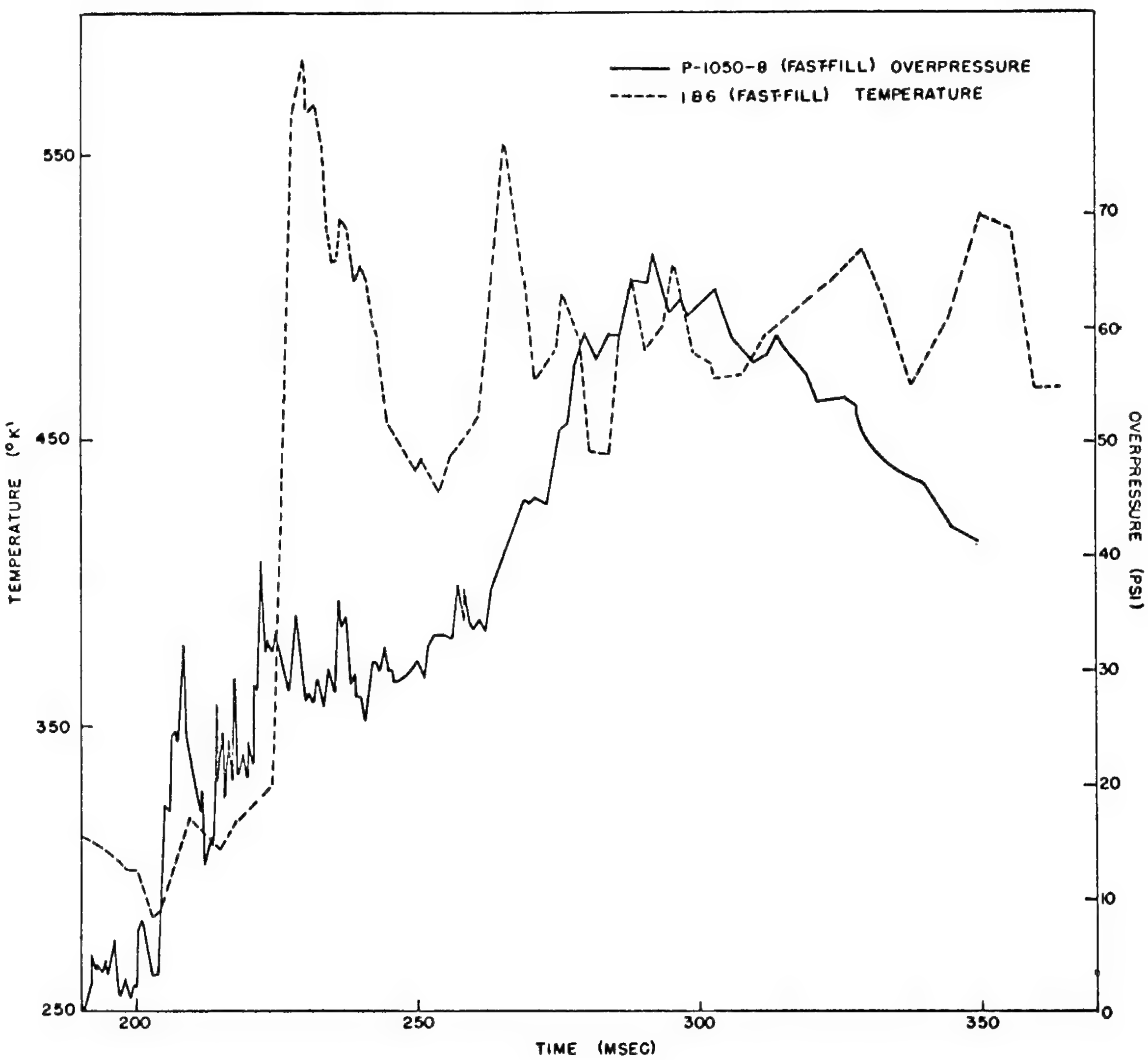
Temperature in fast-fill room, underground personnel shelter, Series I experiments, 1955[7,8]

Figure 53



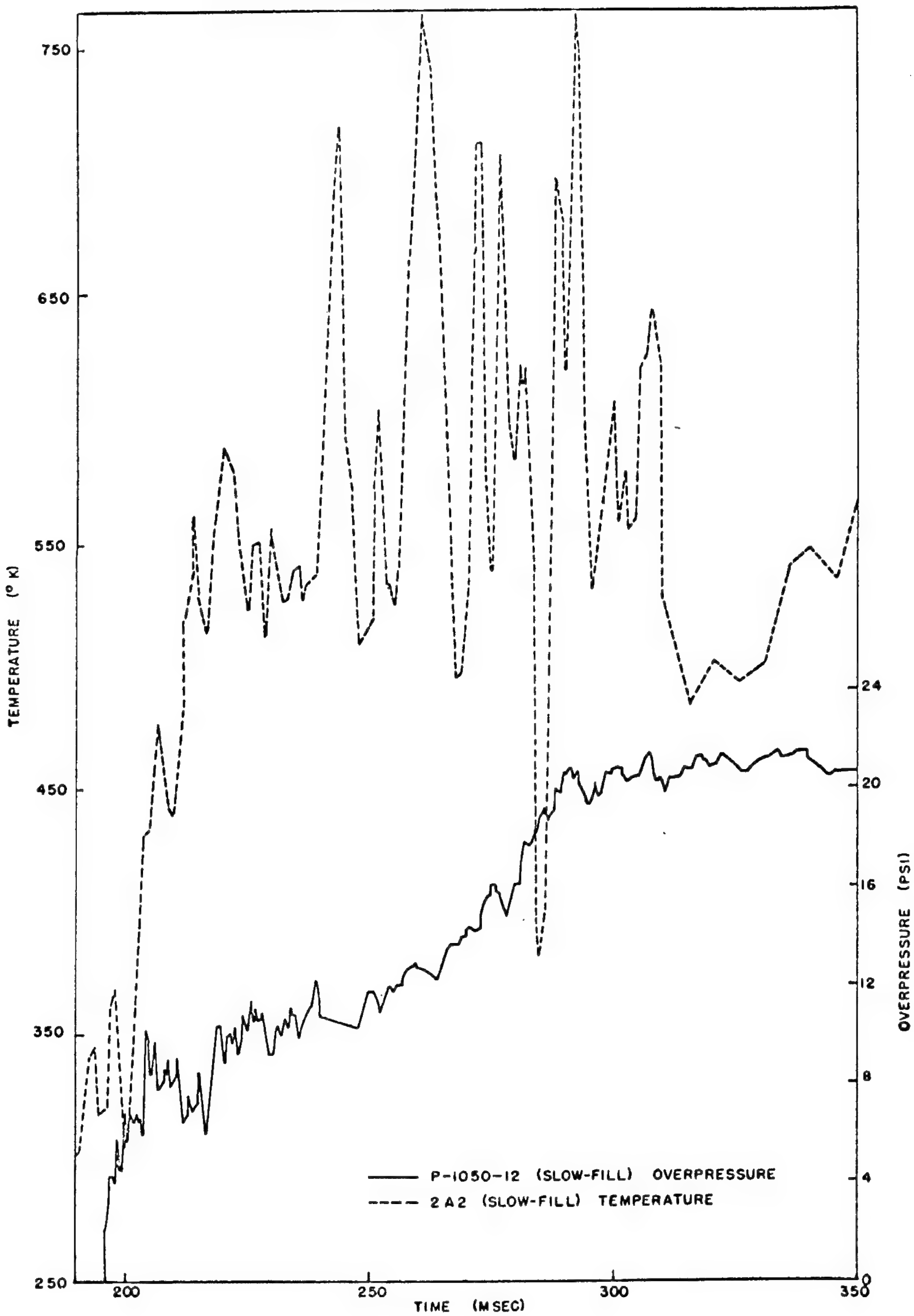
Temperature in slow-fill room, underground personnel shelter, Series I experiments, 1955[7,8]

Figure 54



Temperature and overpressure in fast-fill room, underground personnel shelter, Series II experiments, 1955[7,8]

Figure 55



Temperature and overpressure in slow-fill room, underground personnel shelter, Series II Experiments, 1955[7,8]

Figure 56

the pressure pulse in the fast-fill room, whereas both pulses arrive nearly simultaneously in the slow-fill room, needs only mean that the more complex and longer main entryway into the fast-fill room served initially to cool the hot gases and debris, a circumstance that did not occur as the blast wave moved into the slow-fill room through the vertical and comparatively short escape shaft.

Considerable singeing of the fur of animals as well as burning of the skin of animals exposed in the 1955 group and other shelters was recorded as can be appreciated quickly by noting the appropriately labeled columns in Tables 12 and 14.[4] The most dramatic and serious skin burns occurred to animal Z-1 located in or near the entryway door on the Series II experiments (see position 1, Figure 18). Not only was the fur sufficiently carbonized to leave a dark mark on the wall against which the animal was thrown by the force of the wind as shown in Figure 57, but the harness and considerable area of the animal's skin was burned after the fur had disappeared.

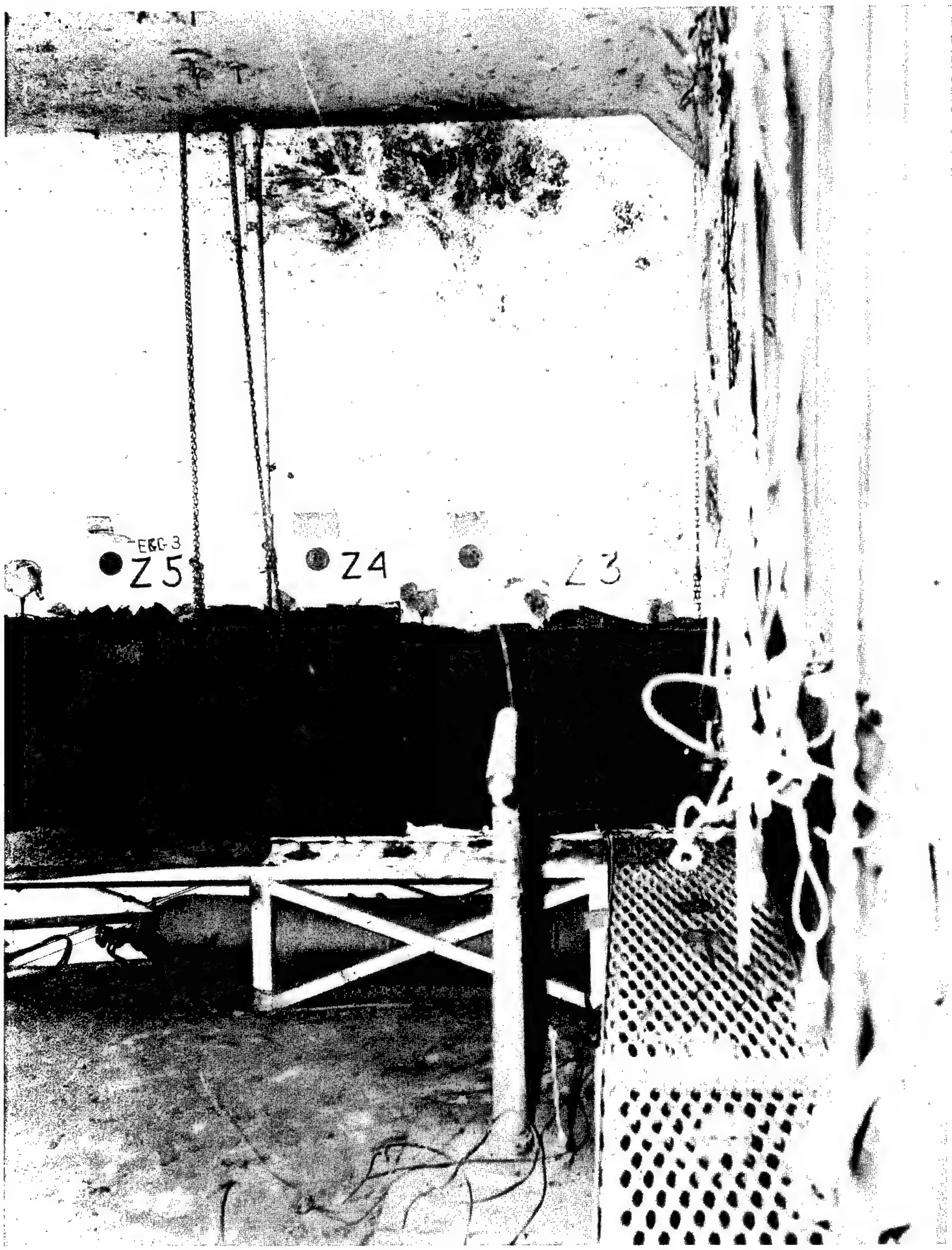
Also significant was the fact that the fur of dogs in the fast-fill room were singed on the room-side of the animals; viz., the side that would have been contacted by the swirling winds.

Unfortunately the temperature-time data are not only too few to correlate with thermal effects in specific animals exposed in the shelter, but they strictly indicate the temperature of the gas near the wall that was aspirated into and through the whistle gauges. What the temperatures were at, or very near, contact between hot, dust-laden gases and the fur and skin of animals may be very much different indeed.

The 1957 Group Shelters

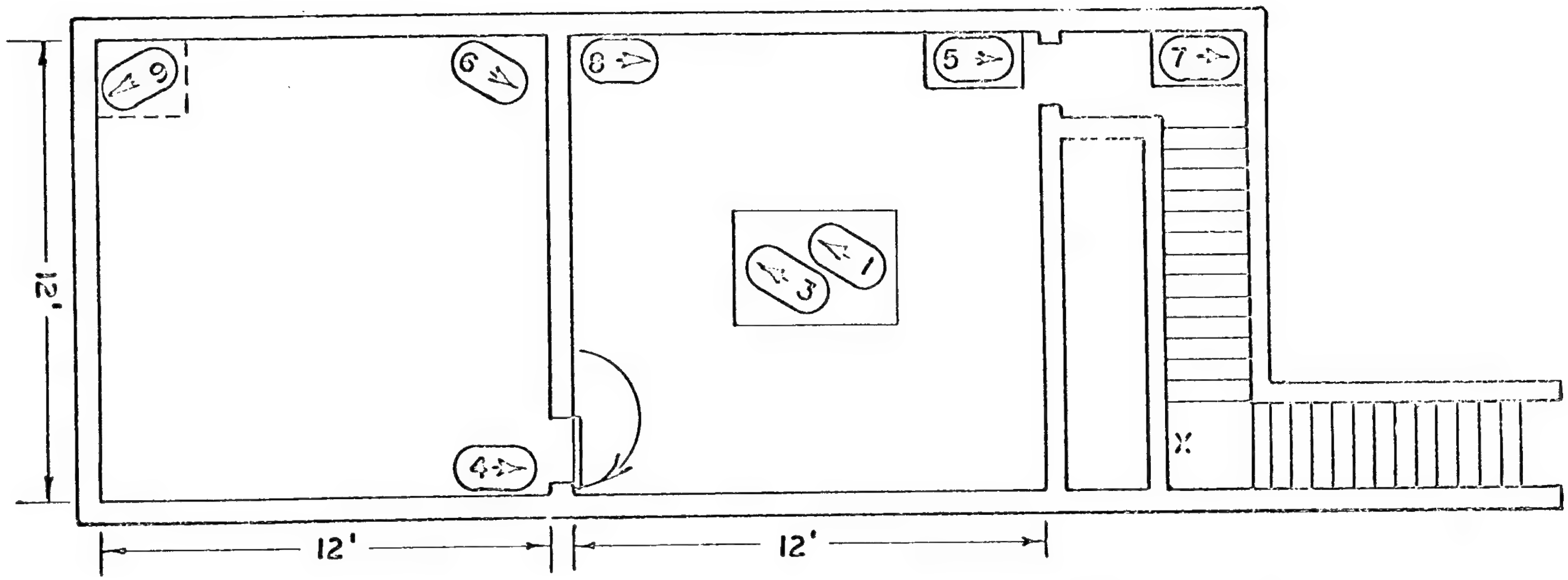
Though instrumentation to record temperature-time data with one-mil thermocouples was arranged by the Civil Effects Test Group in one of the 1957 group shelters (shelter 8002), no records were obtained.[23]

However, eight Chester White pigs were exposed inside this structure at locations noted in Figure 58.[23] The animal at position 7 was severely burned and fatally injured by blast. Animal 5, exposed facing the doorway in a wide-mesh, metal cage to avoid translation,



Imprint due to impact of animal against wall and ceiling; fast-fill compartment of the Series II group shelter, postshot.[4]

Figure 57



Floor plan of the shelter, showing placement of the pigs. The arrow indicates the head of the animal. The stairway was oriented toward GZ. Direct thermal radiation occurred at X on the landing since the top of the tower was on a line of sight from this position.[23]

Figure 58

suffered a third-degree, carbonizing burn of the head and face. Figure 59 is a postshot view of the animal.

All the other pigs escaped thermal damage, even No. 6 exposed directly beneath the escape hatch in the slow-fill compartment. In this regard it is well to recall that the opening above was covered by a perforated, metal plate noted in Figure 60. In all probability this screen-like plate served to reduce the temperature of the debris-laden air as it entered the escape shaft significantly.

No thermal effects were noted in the animals exposed in the 8001 group shelter in 1957 whereas many in the 8002 structure were burned and singed as shown in Table 22.[5] Those interested in the small animal data are referred to reference 5. However, the results for dogs and pigs given in Table 22 can be assessed according to the position of exposure by noting the animal location set forth in Figures 25 and 58 above. It is significant that not only did the baffles used in the shelters minimize or eliminate translation of animals by blast wind, they also served to decrease the severity of thermal burns, an observation that is consistent with the view that hot gases and dust carried into the shelter by the blast is an important factor contributing to the thermal effects observed.

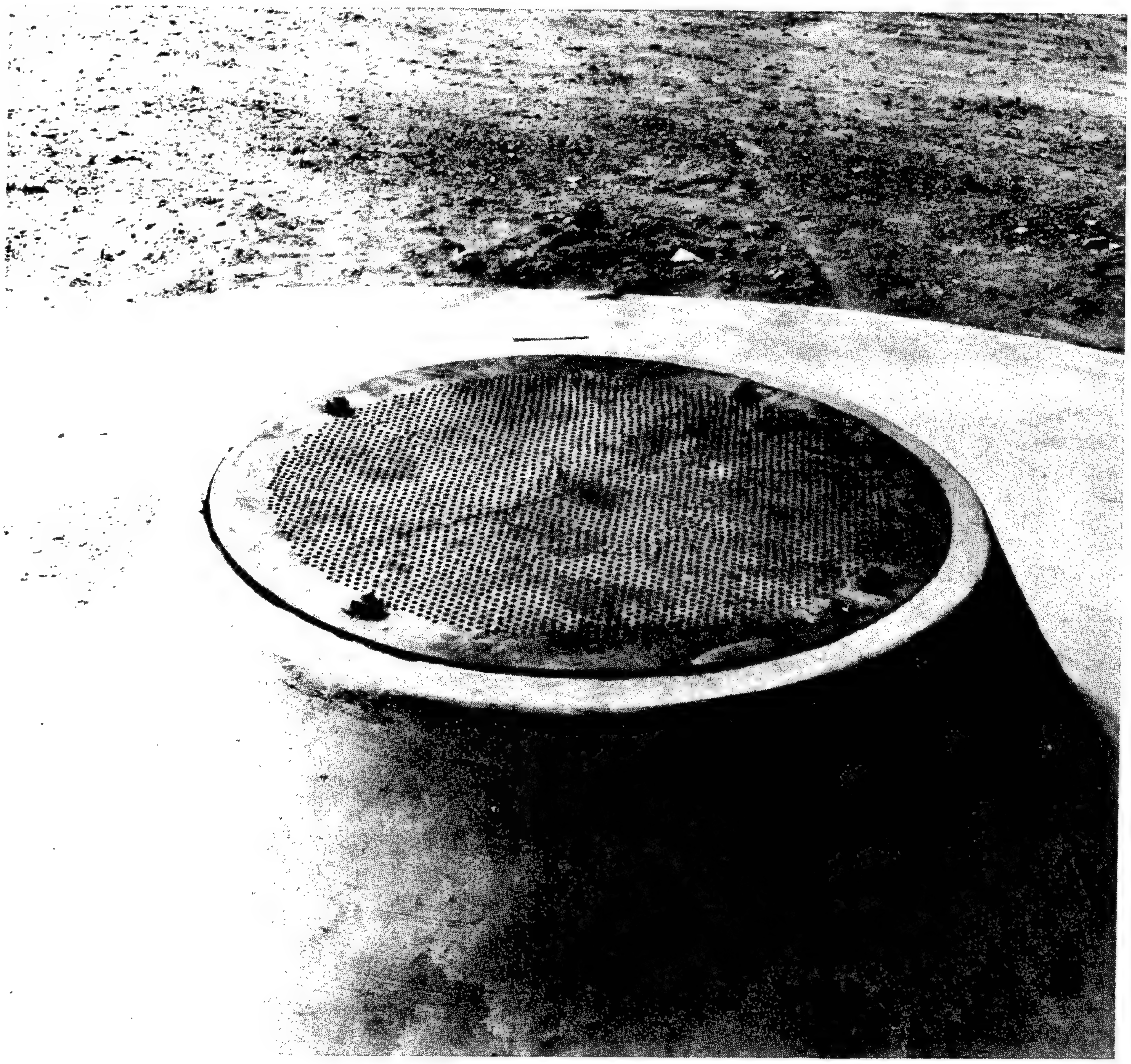
In this regard it is well to point out that the outside pressure-time curve was nearly classical for the 8001 shelter inside which no thermal damage was seen. However, the wave form was atypical for the 8002 structure inside which there was severe burning of animals. Since the maximum pressures inside the shelters were nearly the same* — averaging 25.5 psi for 8001 and 30.3 psi for 8002 — and therefore compressive heating of the air was almost comparable, it follows that some other factor must have been involved in producing high temperatures inside the 8002 shelter.

That this might have involved hot, dust-laden air is indicated

*See Table 15.

Pig 5, showing the carbonized burn of the face and forehead, with singeing of the hair on the shoulders.[23]

Figure 59



Aerodynamic mound with sieve-plate cover (8002)[5]

Figure 60

TABLE 22

TABULATION OF PATHOLOGICAL FINDINGS FOR SHELTER 8002: DOGS, SWINE, RABBITS, AND GUINEA PIGS[5]

Animal No.	Body weight*	Thermal effects	Lung hemorrhage	Lung weight, % of body weight	Eardrum rupture† Right	Eardrum rupture† Left	Remarks
			Dogs				
Fast-fill							
G-1	20.4	First degree burn over scrotum, inner thigh, under both axilla, and about the mouth; extensive singeing	None	0.91	x	x	Translated from shelf without injurious impact
G-2	19.5	Areas of erythema and singeing of hair over hindquarters	None	1.07	x	x	
G-3	20.9	None	None	1.23	x	x	
G-4	22.3	None	None (?)	1.03	x	-	Slight degree of hemorrhage nasal sinus; bilateral and petechial hemorrhage in lung found histologically
G-5	23.2	Slight singeing over entire body	None	0.98	x	-	
G-6	16.8	None	None	1.00	x	x	
G-7	21.4	None	None	1.02	x	x	
G-8	17.7	None	None	1.02	-	-	
	20.3 ± 0.8†			1.04 ± 0.03‡			
Slow-fill							
G-9	19.5	None	None	0.92	x	-	
G-10	16.4	None	None	1.04	-	-	
	18.0 ± 1.55‡			0.98 ± 0.06‡			
			Swine				
Fast-fill							
P-1		None	None		x	-	Small area of contusion lining small intestine
P-3		None	Slight		x	x	
P-5		Carbonized and first degree burns on forehead and ears; hair singed over shoulders and front area of legs	Moderate		x	x	

(continued on next page)

TABLE 22—(Continued)

Animal No.	Body weight*	Thermal effects	Lung hemorrhage	Lung weight, % of body weight	Eardrum rupture† Right	Eardrum rupture† Left	Remarks
			Swine				
Fast-fill							
P-7		First degree burns; singed	Massive		x	x	Dead at recovery; hemothorax, fractured right ribs 6 through 8 and punctured lungs; petechial hemorrhages in pancreas, adrenal fat, and small intestine; subcapsular hemorrhage in spleen
P-8		None	None		NR	NR	
Slow-fill							
P-4		None	None§		-	-	
P-6		None	None§		-	-	
P-9		None	None§		-	-	Died of radiation sickness on D+14
			Rabbits				
Fast-fill							
R-1	2950		None	0.47	-	x	
R-2	2962		None	0.68	x	-	
R-4	2700		None	0.48	x	x	
R-6	2860		None	0.42	NR	NR	
R-8	2500		Slight	0.44	-	-	
R-10	2800		Slight	0.39	x	x	
	2795 ± 71‡			0.48 ± 0.04‡			
Slow-fill							
R-12	2750		None	0.40	-	-	
R-14	2558		None	0.39	x	NR	
R-16	1626		None	0.80	-	x	
R-18	2652		None	0.45	-	-	
R-20	2805		None	0.46	-	-	
R-22	3245		None	0.34	-	-	
R-24	2723		None	0.40	-	-	
R-26	2497		None	0.44	-	-	
R-28	2918		None	0.48	-	-	
R-30	2741		None	0.55	-	-	
	2652 ± 132‡			0.47 ± 0.04‡			
			Guinea Pigs¶				
Fast-fill							
GP-1-1	464	Singed	None	0.73	x	x	
2	328	Singed	None	2.65	x	x	
3	472	Singed	None	0.80	x	x	

(continued on next page)

TABLE 22—(Continued)

Animal No.	Body weight*	Thermal effects	Lung hemorrhage	Lung weight, % of body weight	Eardrum rupture† Right	Left	Remarks
GP-2-1	453	Slight singeing	Slight	0.95	x	x	
2	383	Slight singeing	Slight	1.17	x	x	
3	434	Slight singeing	Slight	1.06	x	x	
GP-3-1	418	None	Slight	0.96	x	x	
2	438	None	None	0.96	x	x	
3	514	None	Slight	0.88	x	x	
GP-4-1	497	None	Slight	0.88	x	x	
2	494	None	Slight	0.85	x	x	
3	470	None	Slight	0.98	x	x	
	447 ± 15‡			1.07 ± 0.15‡			
Slow-fill							
GP-7-1	378	None	None	1.32	-	-	
2	448	None	None	0.94	-	-	
3	451	None	None	0.93	-	-	
GP-8-1	453	None	None	0.93	-	-	
2	471	None	None	0.85	-	-	
3	460	None	None	1.00	-	-	
GP-9-1	456	None	None	1.03	-	-	
2	430	None	None	0.91	-	-	
3	483	None	None	0.72	-	-	
GP-10-1	492	None	None	0.85	-	-	
2	463	None	None	0.86	-	-	
3	437	None	None	1.12	-	-	
	452 ± 8‡			0.86 ± 0.05‡			

*Body weights are in kilograms for dogs and in grams for guinea pigs and rabbits.
†x, -, and NR indicate that the eardrums were ruptured, intact, or not readable, respectively.
‡Mean and standard error of the mean.
§Saved for observation of radiation effects.
¶There were 2 animals saved from each cage (Nos. 4 and 5) for observation of radiation effects.

TABULATION OF PATHOLOGICAL FINDINGS FOR SHELTER 8002: MICE

Cage No.*	Mortality	Thermal effects	Lung hemorrhage
Fast-fill			
1	14/20	20/20 burned and singed	18/20
2	1/20	9/20 singed; 2/20 burned	7/20
4	0/20	0/20	1/20
Slow-fill			
8	0/20	0/20	0/20
10	0/20	0/20	0/20

*Saved all 20 mice from cages 3, 7, and 9 for radiation effects.

by the fact that the disturbed wave form occurring outside Shelter 8002 was due to heating of the ground by the fireball. This effect was sharply minimized by the use of massive amounts of lead shielding in the tower on the shot to which Shelter 8001 was exposed, an event which tended to avoid heating the air, dust and ground surface outside and forward of the structure. Thus hot dust simply was not there to be carried inside the shelter and "deliver" calories to the biologic material exposed therein.

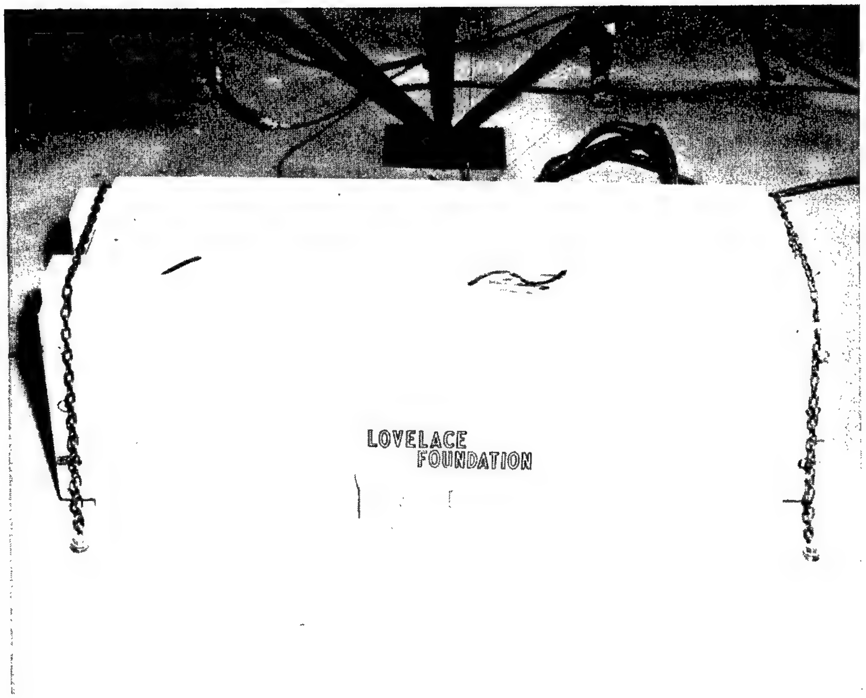
E. The Occurrence of Dust and Other Particulates

Because it was known that dust inside blast protective shelters had, under certain conditions, been lethal to occupants during World War II[24] and it was thought gross and microscopic spalling might occur in closed and buried structures exposed to nuclear blast, exploratory work was undertaken during the 1957 field operation at the Nevada Test Site[21,25] with two objectives in mind; namely, first, to learn whether various sized dust and larger particulates would spall from the walls of subsurface structures; and second, in the case of the larger particulates, to learn whether their velocities might be high enough to be hazardous. A brief summary of selected portions of the relevant data are summarized below.

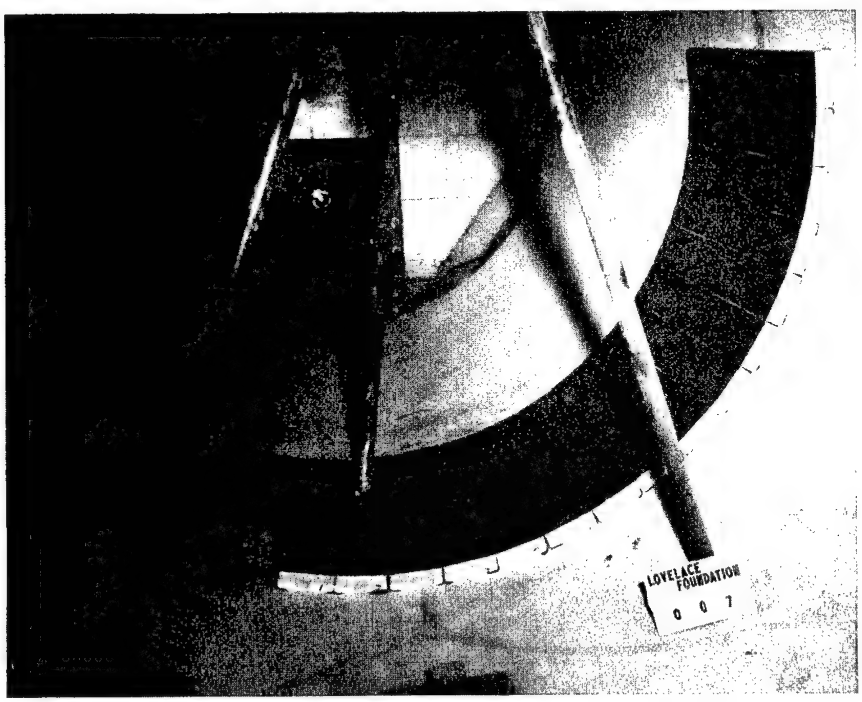
1. Missile Traps in Closed Shelters (1957)

Missile traps or missile-absorbing material as shown in Figure 61 were installed in 4 arch-type[26] and 3 conduit-type[27] concrete shelters during the 1957 test series.[21] The shelters were located 860 to 1360 ft from ground zero as noted in Table 23 which also includes the thickness of ceiling, walls and earth cover for each shelter along with the maximum incident overpressure that passed over each shelter location after the detonation.

Though there were pieces of concrete as large as 0.75 cm in diameter, as seen in Figure 62 recovered from "sticky" trays placed in the forward arch structure (199 psi), and, as Figure 63 shows, 0.5 cm concrete fragments and 1 cm long slivers of wood from the forward concrete-conduit shelter (126 psi), no similar missiles moved towards any of the missile traps with sufficient velocity to become embedded in the absorber.[25] The



Typical trap installation in arch type shelters.[21]



Typical installation of missile absorber in conduit type shelters.[21]

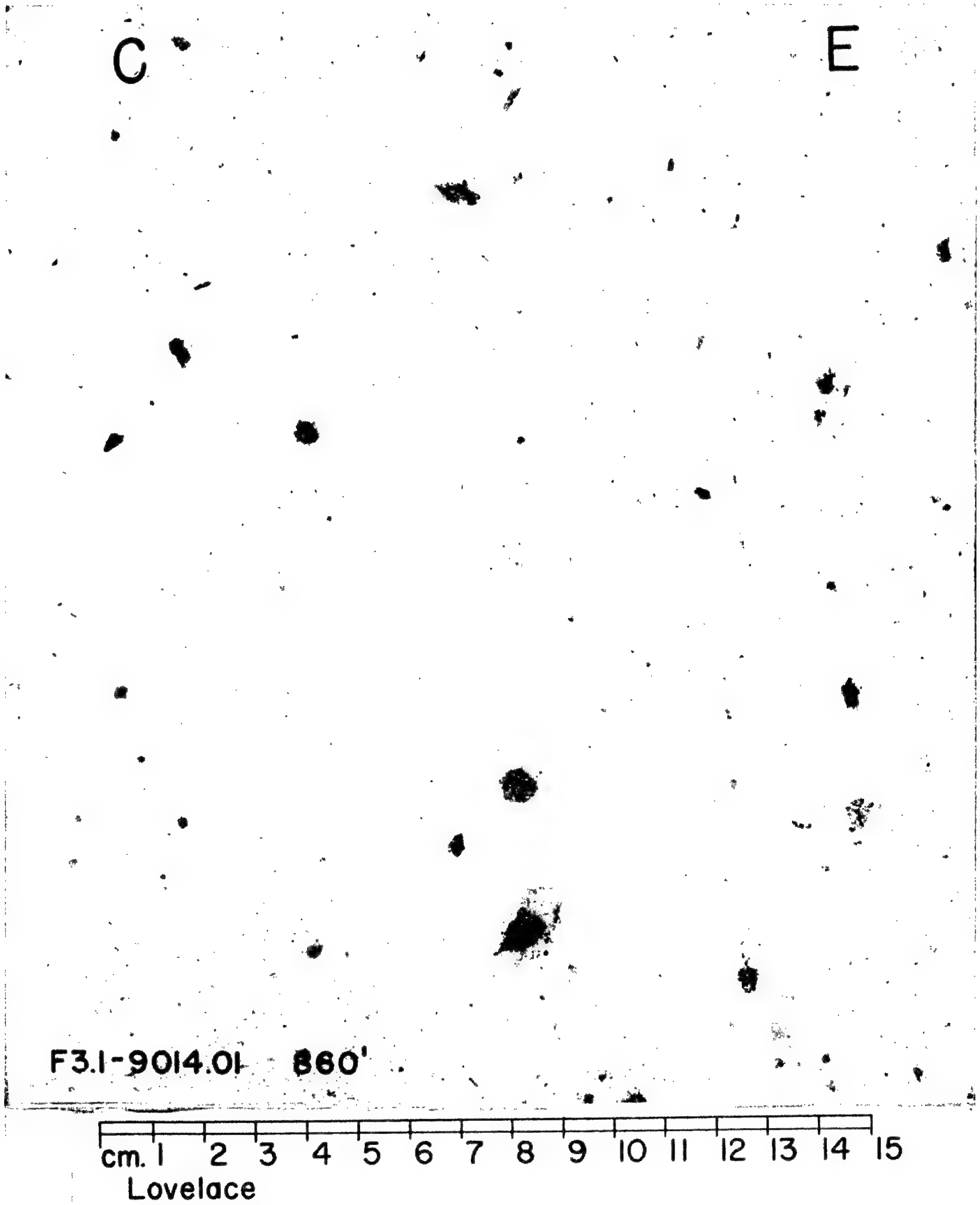
Figure 61

TABLE 23

SUMMARY OF CONCRETE ARCH AND CONDUIT STRUCTURES IN WHICH 1957-MISSILE STUDIES WERE CONDUCTED[21, 26, 27]

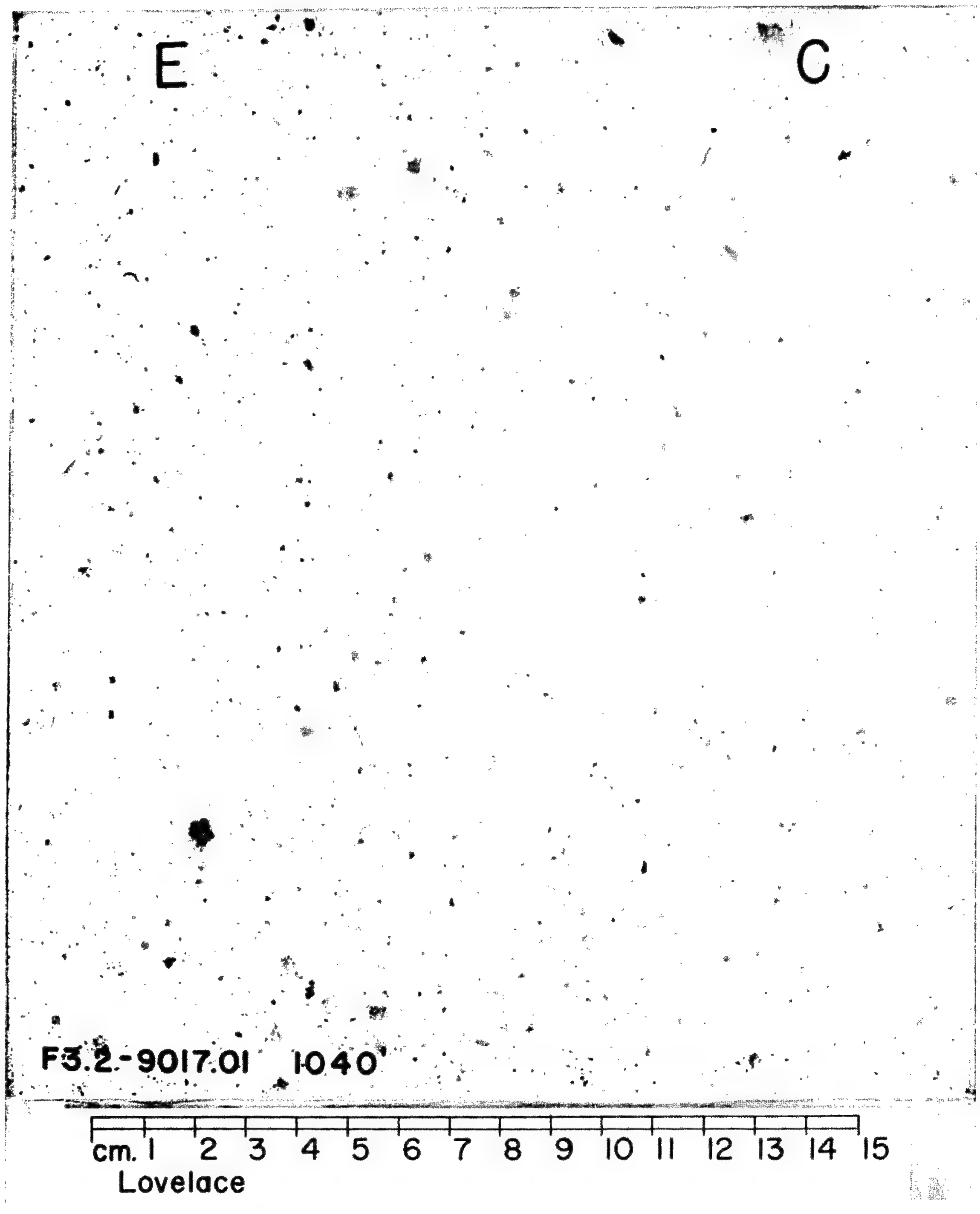
Structure No.	Type of Structure	Ceiling and Wall Thickness in.	Earth Cover ft	Range ft	Maximum Incident Pressure psi
F3.1-9014.01	Concrete arch	8	4	860	199
F3.1-9014.02	Concrete arch	8	4	1040	124
F3.1-9014.03	Concrete arch	8	4	1360	56
F3.1-9015	Concrete arch	8	4	1360	56
F3.2 2-9017.01	Concrete conduit*	8.5	7.5	1040	126
F3.2 2-9017.02	Concrete conduit*	8.5	7.5	1150	100
F3.2 2-9017.03	Concrete conduit*	8.5	7.5	1360	60

*Structures had timbered ends.



Type B dust collector from concrete arch shelter F3. 1-9014.01 (Priscilla)[25]

Figure 62



Type B dust collector from concrete circular shelter F3.2-9017.01 (Priscilla).[25]

Figure 63

threshold velocity for the absorber used (Styrofoam II) is, among other things, a function of the missile mass. However, calibration data show that detectable penetration occurs at about 70 ft per second for 1-gm particles having the density of window glass, 50 ft per second for 5-gm and 45 ft per second for 10-gm particles.

Thus, one may conclude that in the shelters, particles or missiles arising from the ceilings and walls having masses ranging from 1 - 10 gm were moving at velocities slower than 70 and 45 ft per second for the lighter and heavier missiles, respectively.

2. The Fluorescent Particle Study (1957)

Four subsurface structures, tested "closed" during the 1957 operation at the Nevada Test Site, were selected for special study to determine whether any particulates found postshot on floor-mounted sample trays might arise from the walls and ceilings of the shelters.[25] Except for the floor, the inner surfaces of these structures were treated preshot with a 50/50 water-alcohol solution containing 0.1 per cent Fluorescein Sodium.* During the application of dye with rollers, the floors of the shelters were covered to avoid contamination of floor dirt, a precaution to ensure that any fluorescent particles collected on "sticky" trays postshot would have had their origin from wall and/or ceiling spalling rather than from material on the floor.

The four shelters involved, designated RAa, CAb, RAd, and RCb — or 8008, 8012, 8013 and 8015, respectively — are among those shown in Figure 64. In each structure, two types of covered collector trays were cemented to the floor in locations shown in Figures 64 - 68, inclusive. One of these, designated "sticky tray collectors single" in

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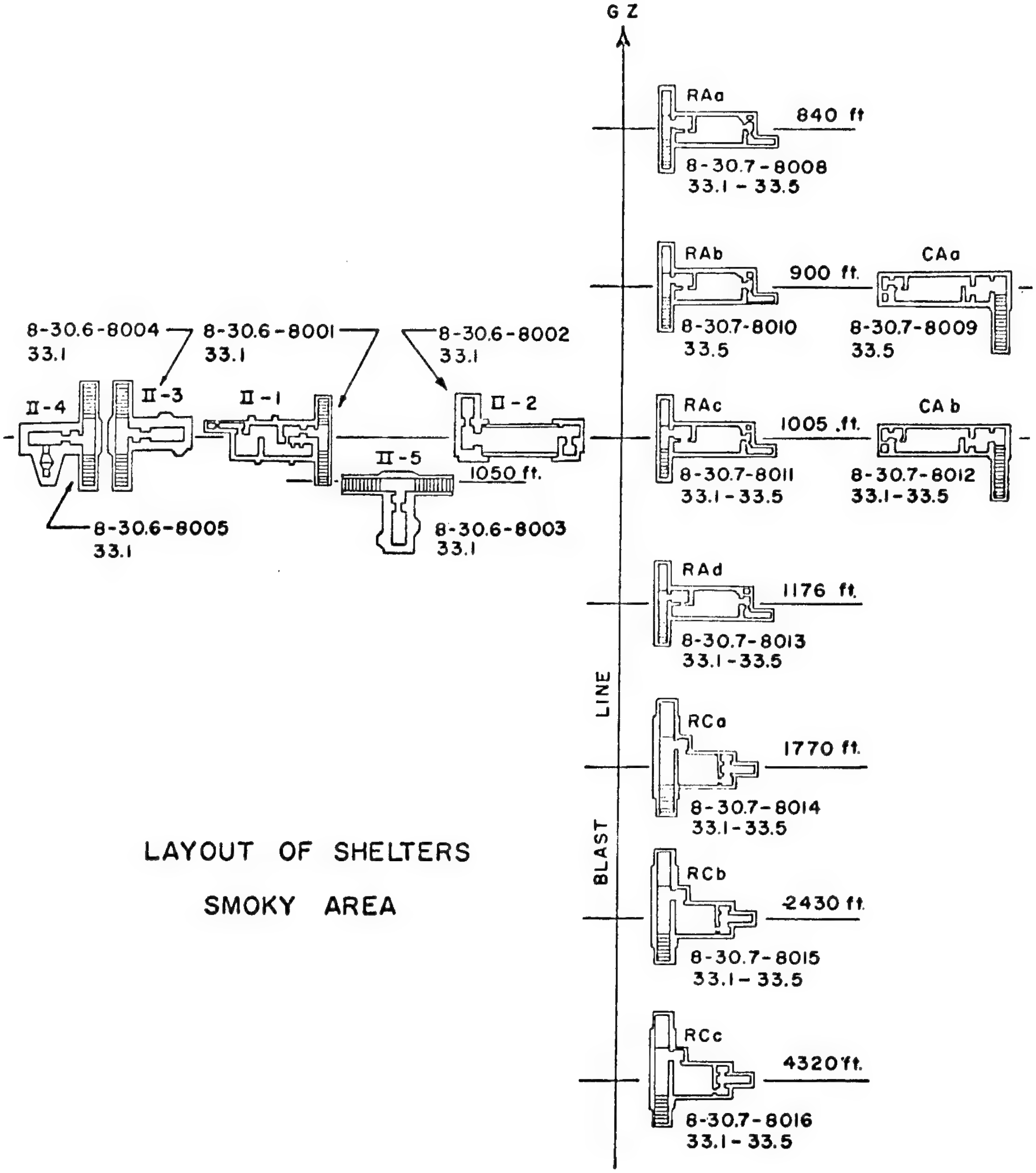
*Selection of the dye and preshot investigations concerning quenching and dequenching techniques were worked out by Dr. Thomas L. Chiffelle, Lovelace Foundation, and Dr. Frederic C. Hirsch, then at Sandia Corporation, now at Argonne National Laboratory. Dr. Hirsch also carried out all the postshot investigations using the material received from the shelters.



Layout of Smoky shelters.[25]

Figure 64

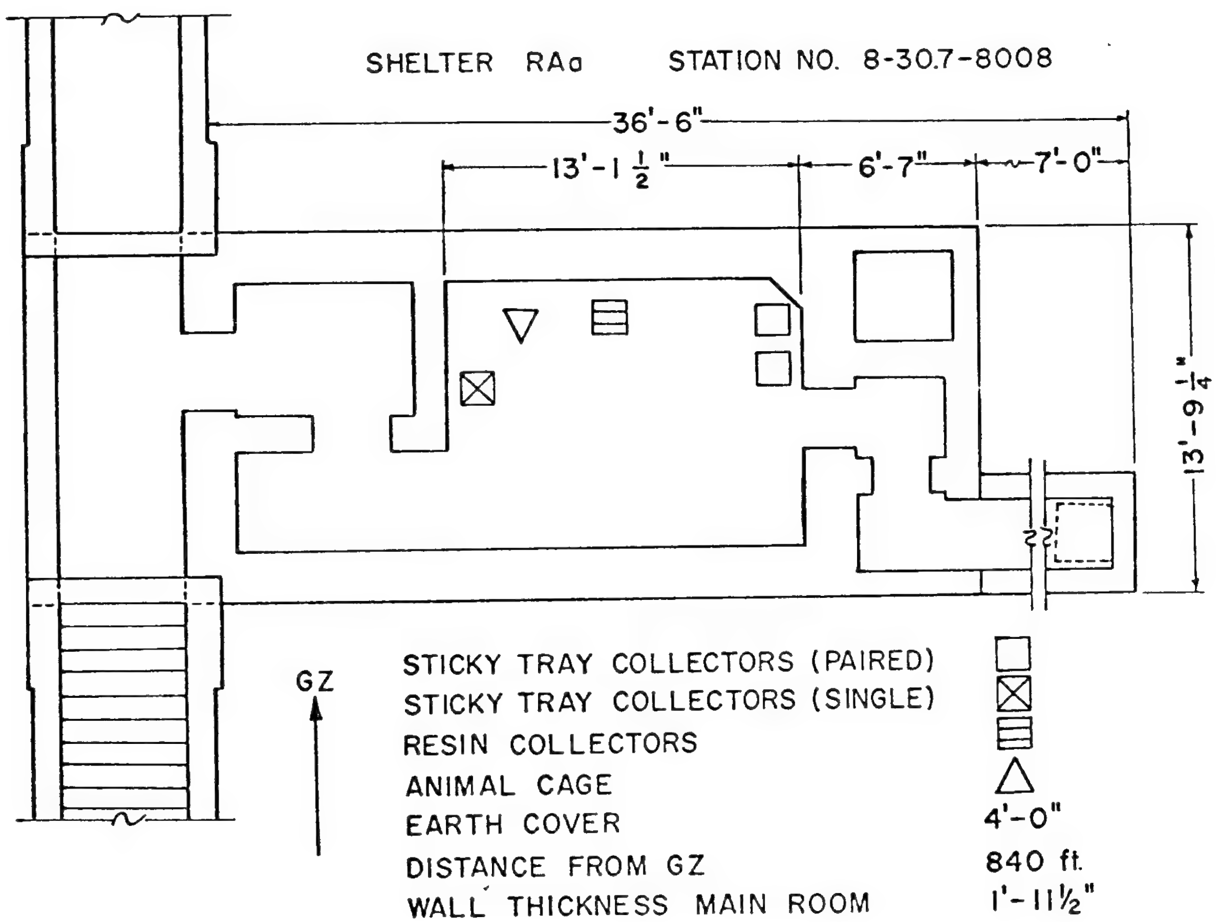


Diagram of structure RAa (Smoky)[25]

Figure 65

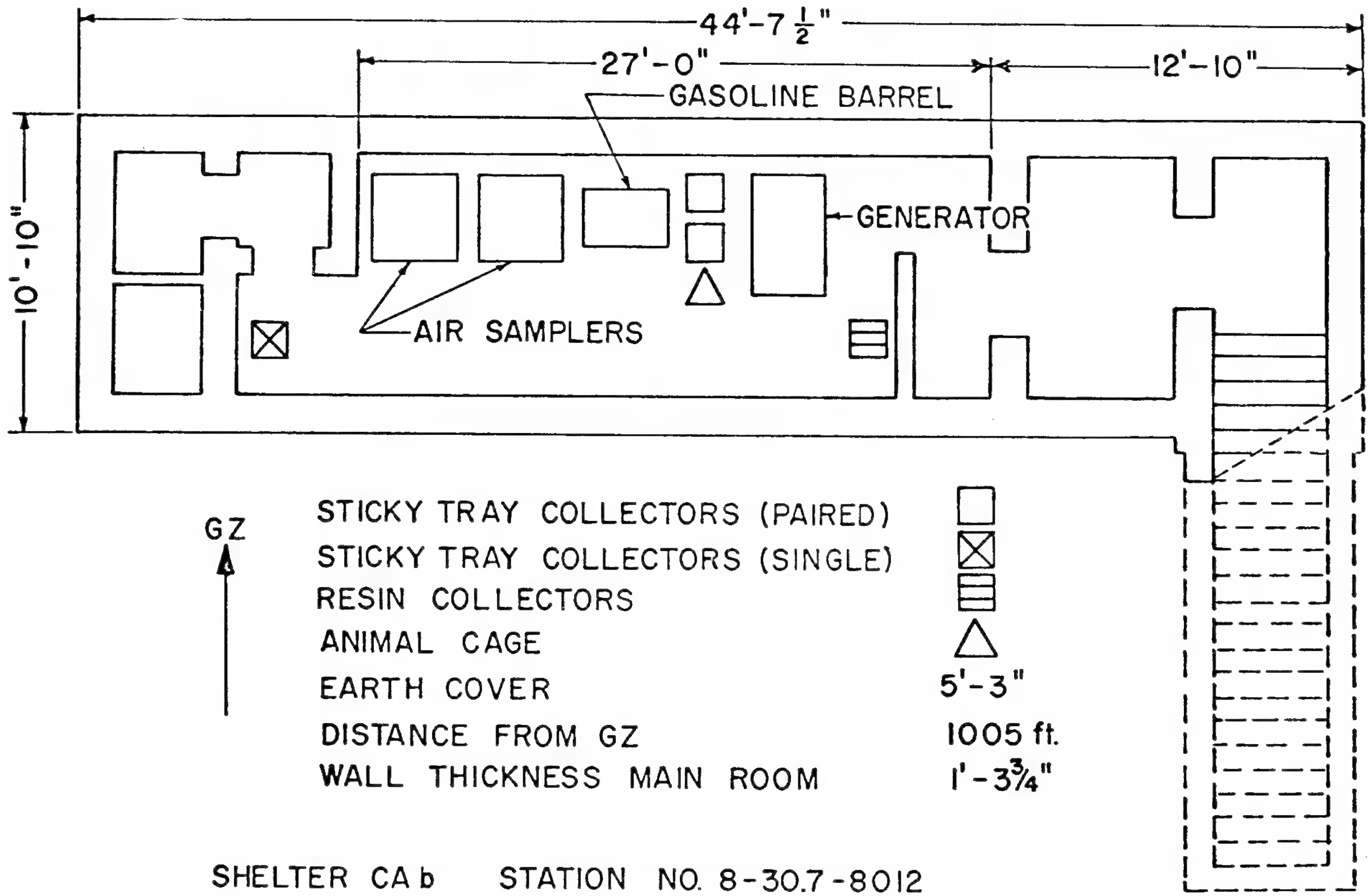


Diagram of structure CAb (Smoky)[25]

Figure 66

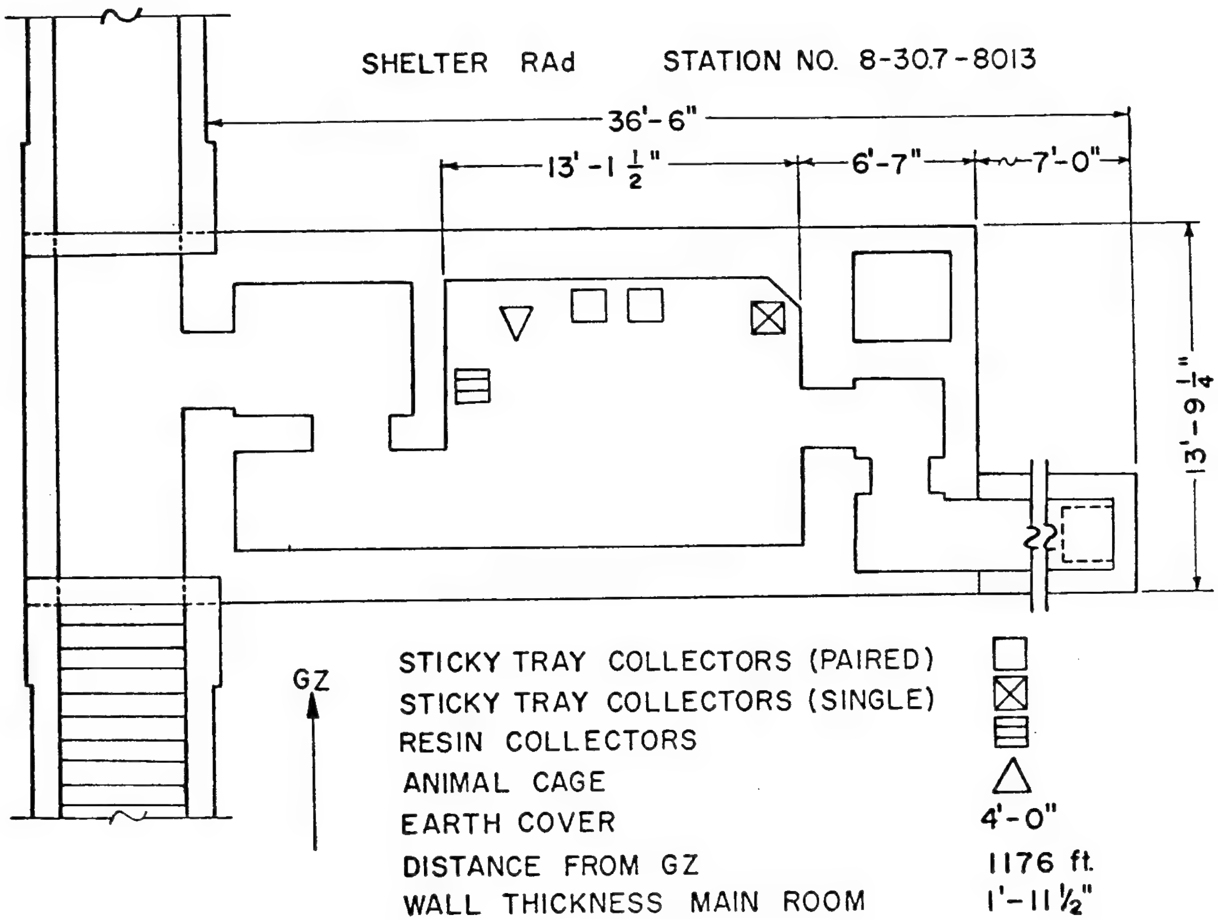


Diagram of structure RAd (Smoky)[25]

Figure 67

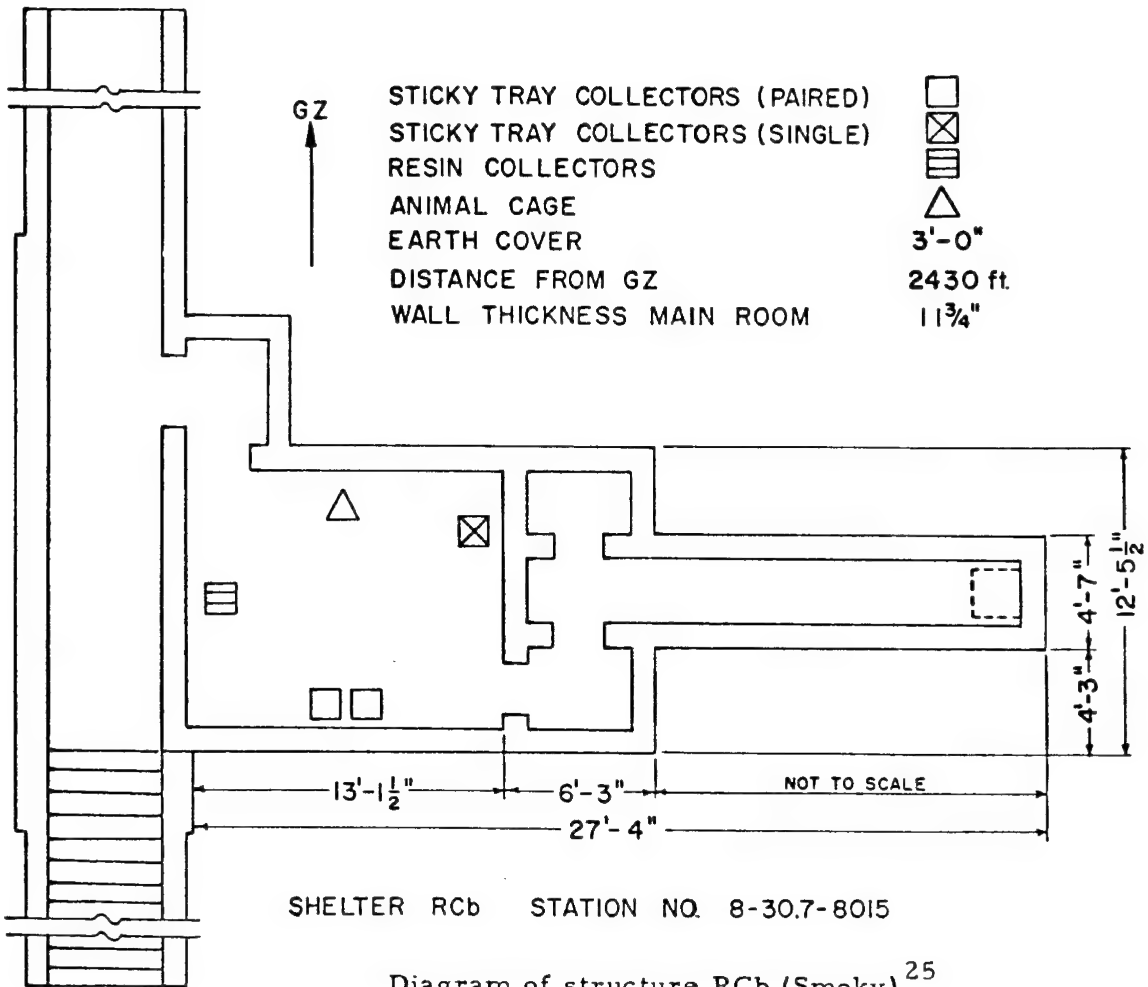


Diagram of structure RCb (Smoky)[25]

Figure 68

the figures, was prepared by affixing transparent sticky paper* to the tops of 12" x 12" aluminum trays with masking tape. The other type collector was prepared by using a nasal atomizer to spray the bottom of a 12-in. square aluminum tray with alkyl resin in a solution of toluene (1 part resin to 4 parts toluene). The trays in shelters RAa-8008 and RAd-8013 were uncovered on D-3, but those located in Shelters CAb-8012 and RCb-8015 were uncovered on D-1. All the shelters except RAa were vacuum-cleaned preshot, CAb and RAd on D-1 and RCb on D-2. Each structure was "buttoned up" on D-1. All the resin collectors and sticky paper preparations were covered with dummy trays and recovered postshot on D+2.

Sticky Resin Trays[25, 28]

Upon return to base camp, the sticky resin-coated trays were illuminated with ultraviolet light. No fluorescent particles were seen. However, in line with preliminary investigations in the laboratory preshot, each tray was held over a beaker of hot glycerine, a procedure that "activated" or "dequenched" the dye. Subsequent illumination with ultraviolet light revealed small fluorescent particles visible to the naked eye on all the collector trays.

These varied in number from 20 to 50 and were more apparent on the tray from Shelter RCb located 2430 ft from ground zero than they were on trays from the 3 more forward structures. It was thought at the time that this finding might, in part at least, be due to the difference in wall and ceiling thicknesses — about 1 ft for RCb shelter and near 2 ft for the other 3 — along with differences in earth cover — 3 ft for the RCb shelter and 4 to 5 ft for the near structures — even though there were great differences in the wave form of the air pressure pulse that moved over each shelter station as well as the maximum incident overpressure associated therewith. That the latter ranged from 11.5 psi

*Suggested by and obtained through the courtesy of Dr. Kermit H. Larsen, University of California, Los Angeles, who had used the technique for collecting fallout over a number of years.

to 175 psi is noted in Table 24 along with some of the facts set forth above. Also, Figure 69 allows one to appreciate the changes in wave form that occurred from 840 to 2589 ft from ground zero, a range slightly greater than the farthest structure studied which was located at 2430 ft.

Since postshot follow-on work in the laboratory using the sticky paper collectors showed a different distribution of grossly apparent particulates among the shelters as will be noted below, it is now apparent that the differences in location of the two types of trays in the shelters, as can be appreciated by looking at Figures 65 - 68, the presence or absence of grossly apparent cracks in the ceiling above the two different collectors and the proximity of each to the ventilation inlet duct located in each shelter on the wall nearest the escape hatches, all probably contributed in some undefined and unknown way to the pattern of data observed.

At least it can be said that the resin-tray results established that many of the particulates found postshot actually came from the walls and/or ceilings of the shelters, but these data "say" nothing about the mechanism involved in loosening the particles from the inner surface of the structures.

Sticky-Paper Trays (Single)*

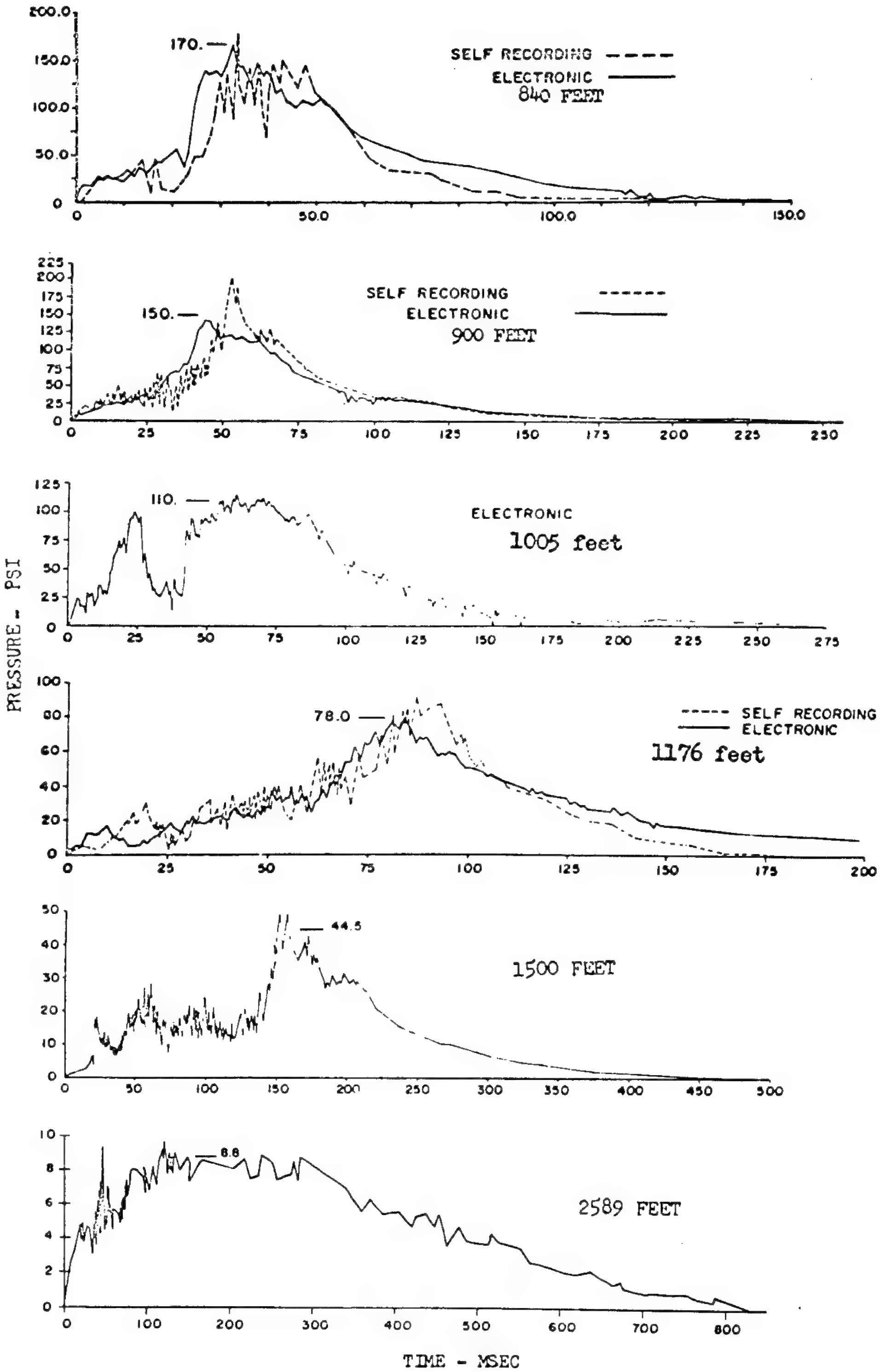
Postshot laboratory work involving the sticky-paper trays included a number of procedures.[25,28] First, the papers were recovered from the trays, cut into pieces large enough to span an aperture measuring 25 x 38 mm (9.50 cm^2) which was cut in a metal plate the shape of a microscopic slide. The paper, sticky side down, was taped to the latter with Scotch tape. Two dequenching procedures were tried. The first, involving the use of an atomizer to spray the preparation with a mixture of equal parts of glycerine, methanol and water, did not prove very satisfactory. The second method was much more effective and simpler; namely, holding the paper-slide combination over boiling methanol.

*The data included in this section were kindly made available by Dr. Frederic C. Hirsch, who carried out the postshot analytical work at the Lovelace Foundation, Albuquerque, New Mexico.[28]

TABLE 24

SUMMARY OF DATA REGARDING SHELTERS USED IN THE 1957 FLUORESCENT DYE STUDIES[9, 25]

Shelter Designation	Type of Structure	Ceiling and Wall Thickness in.	Earth Cover ft	Range in ft	Maximum Incident Pressure psi
RAa 8-30.7-8008	Concrete Rectangular	1'11-1/2"	4	840	175
CAb 8-30.7-8012	Concrete Cylindrical	1'11-1/2"	5.25	1005	116
RAd 8-30.7-8013	Concrete Rectangular	1'11-1/2"	4	1176	81
RCb 8-30.7-8015	Concrete Rectangular	11-3/4"	3	2430	11.5



Blast-line pressure-time data — Smoky event[9]

Figure 69

After the dequenching procedure, the papers were illuminated with ultraviolet light and viewed using an ultraviolet-light microscope. The entire aperature of 9.50 cm^2 was scanned for each of 6 such slides prepared using the sticky papers recovered from the 4 shelters studied. Grossly apparent particulates were counted and though it was not possible using the fluorescence from ultraviolet illumination to size the particles accurately, it proved feasible to count those that had diameters (a) smaller than 5 microns (b) approximately 5 microns and (c) larger than 10 microns. The data are tabulated and summarized in Table 25.

Macroscopic particles of concrete that showed fluorescence on each 12-in. square plate totaled 112, 20 and 6 for the 8012, 8013 and 8015 shelters, respectively.*

Fluorescent microscopic particles counted summed to 26,874. These ranged in number from 256 to 19,358 among the 4 shelters, and on the basis of the average number per unit area, the spread was from 4.5 to 340 particles per cm^2.

As for size, the average figures show that 36, 56 and 8 per cent of the particulates were less than 5 microns, approximately 5 microns and greater than 10 microns, respectively. Though there is considerable variability in the distribution of particles between the group labeled about 5 microns (26 - 65 per cent) and less than 5 microns (24 - 69 per cent), there is a remarkable consistency in the distribution if the data are grouped to show the number of particulates less than 10 microns as tabulated below.

Shelter	Particles Less than 10 Microns	
	Number	Per Cent of Total
8008	238	93.0
8012	17705	91.5
8013	6314	94.7
8015	527	88.6

*No record was made of the macroscopic count in the 8008 shelter.

TABLE 25

TOTAL NUMBER AND APPROXIMATE SIZE DISTRIBUTION OF MACROSCOPIC AND MICROSCOPIC FLUORESCENT PARTICLES RECOVERED FROM STRUCTURES TREATED WITH FLUORESCENT DYE[25, 28]

Structure Designation	Vacuum Cleaned Preshot	Dequench-ing Technique	No. Fluorescent Macroscopic Concrete Particles*	Slide No. **	No. Fluorescent Particles Having Indicated Count Diameters in Microns <5	Approx. 5	>10	Total	Average No. Particles Per cm^2
RAa-		Glycerine	-	1	9	32	6	47	
8008	No	Methanol		2	19	20	1	40	
		Water		3	20	35	4	59	
		Spray		4	13	26	3	42	
				5	6	29	3	38	
				6	5	24	1	30	
				Total	72	166	18	256	4.5
				Per Cent	28	65	7	100	
CAb-									
8012	Yes	Methanol	112	1	768	2016	448	3232	
		Vapor		2	830	2076	287	3193	
				3	770	2281	31	3082	
				4	682	2216	511	3409	
				5	687	2092	343	3122	
				6	963	2324	33	3320	
				Total	4700	13005	1653	19358	340
				Per Cent	24	67	9	100	

(continued next page)

TABLE 25 (Continued)

Structure Designation	Vacuum Cleaned Preshot	Dequenching Technique	No. Fluorescent Macroscopic Concrete Particles*	Slide No. **	No. Fluorescent Particles Having Indicated Count Diameters in Microns				Average No. Particles Per cm^2
					<5	Approx. 5	>10	Total	
RAd-8013	Yes	Methanol	20	1	778	270	32	1080	
		Vapor		2	779	344	22	1145	
				3	785	270	67	1122	
				4	713	248	119	1080	
				5	734	274	88	1096	
				6	776	343	23	1142	
				Total	4565	1749	351	6665	117
				Per Cent	69	26	5	100	
RCb-8015	Yes	Methanol	6	1	27	56	23	106	
		Vapor		2	16	43	14	23	
				3	65	53	14	132	
				4	75	37	6	118	
				5	39	26	5	70	
				6	62	28	6	96	
				Total	284	243	68	595	10.4
				Per Cent	48	41	11	100	

(continued next page)

TABLE 25 (Continued)

Structure Designation	Vacuum Cleaned Preshot	Dequenching Technique	No. Fluorescent Macroscopic Concrete Particles*	Slide No. **	No. Fluorescent Particles Having Indicated Count Diameters in Microns				Average No. Particles Per cm^2
					<5	Approx. 5	>10	Total	
Summary									
8008	No	Spray	--		72	166	18	256	4.5
8012	Yes	Vapor	112		4700	13005	1653	19358	340
8013	Yes	Vapor	20		4565	1749	351	6665	117
8015	Yes	Vapor	6		284	243	68	595	10.4
		Totals	138		9621	15163	2090	26874	
				Per Cent	36	56	8	100	

*Apparent on a 12-x-12 in. sticky paper preparation.

**The area scanned on each slide was 9.50 cm^2.

Though the many variables involved make it unwise to attempt any further detailed analysis of the data, at least two conclusions can be drawn from the information in Table 25. First, particulates arising from the walls and/or ceilings of the underground shelters studied did appear after the structures were exposed to blast-induced ground shock. Second, a high percentage of these particles were quite small, being less than 10 microns in diameter.

3. The Dust Study (1957)

General

Also during the 1957 series, dust samples were taken inside all the structures listed in Table 23 as well as those shown on the right-hand side of the blast line in Figure 64. What was done will be described and sample results will be given for the shelters shown in Figures 65 - 68, inside which the fluorescent particle study was carried out.[25,28]

Paired sticky-paper trays were installed at locations designated in Figures 65 - 68 as "sticky tray collectors paired" on D-14. Two equal-sized rectangular papers protected each sticky tray. One of these was stripped off on D-14 and the uncovered side of this tray was labeled "C" for control. The other side of the tray, uncovered on D-3 for Shelters 8008 and 8013 and on D-1 when Shelters 8012 and 8015 were "buttoned up," was labeled "E" for experimental.

At recovery the trays were mated, the "E" to "E" and "C" to "C" portions, thereby "trapping" the material on the trays between the two opposing sticky sides of the preparation. Thus, the control portion of the preparation held pre- and postshot dust while the experimental side only postshot dust. The paired papers were stripped from the trays, their edges taped and sent to the laboratory for study.

Subsequently, two procedures of interest were carried out. First, eight 1"-x-3" (19.3 cm^2) samples were cut from each of the paired papers using a template prepared for this purpose. Each sample was individually weighed and the average amount of dust determined in mg/cm^2 by subtracting the average weight of paired, but uncontaminated sticky papers. Following this, the average dust concentrations in gm/cubic meter were

calculated assuming the average figure for each shelter represented all the dust that fell from the air in a column above the sample tray.

Second, particle-size determinations were made using a Zeiss microscope fitted with a calibrated ocular micrometer and Patterson Globe and Circle Graticule, calibrated for the magnifications used. Counts of 100 particles were made from each preparation. They were divided into 5 groups according to particle diameter; viz., $<0.5\mu$, $0.5 - 1.9\mu$, $2 - 5.9\mu$, $6 - 10\mu$, $>10\mu$.

Results

Table 26 includes the average weight data and the calculated concentrations for postshot dust obtained using the experimental sides of the paired, sticky trays. The average concentrate of dust estimated ranged from 2.0 to 5.5 gm/cubic meter. It is not known why the concentration in Structure 8013 (5.5 gm/m^3) at a range of 1176 ft was higher than for Shelter 8008 (3.4 gm/m^3) located at a range of 840 ft. On the one hand, either the data may be innately variable because of the contribution made by particles falling from spurious cracks in the ceiling, or they may be influenced by differences in preshot activity in the shelters that occurred between the time the sticky trays were uncovered and the structures were actually "buttoned up." On the other hand, there may well have been real variations in the spalling characteristics of the structures or, more likely, a variation in the amounts of dust blown through the sand traps protecting the ventilation system of the structures.

The distributions of particle sizes are shown in Table 27 and the average data for postshot and postshot-plus-preshot dust are shown in Figure 70. Because of the nature of the data and the variables involved, it is not possible to say whether the shift in particle-size distribution towards the smaller sizes noted in the postshot samples compared with the samples containing pre- and postshot dust is real or not. In any event, it is clear that very close to half of the particles in most shelters were 10 microns or below in diameter.

TABLE 26

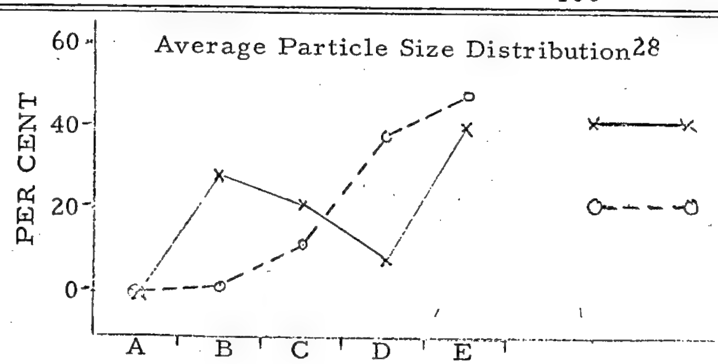
DUST DATA FROM 8008 SERIES SHELTERS (1957)[28]

Structure Designation	Average Gross Weight Paired Sticky Tray mg/cm^2	Average Net Weight Paired Sticky Tray mg/cm^2	Average Net Weight Single Sticky Paper gm/m^2	Maximum Ceiling Height		Estimated Dust Concentrations gm/m^3
				Inches	Meters	
RAa-8008	16.58	1.56	15.6/2	90.5	2.30	3.4
CAb-8012	17.20	2.18	21.8/2	98.5	2.50	4.4
RAd-8013	17.56	2.54	25.4/2	90.5	2.30	5.5
RCb-8015	15.80	0.78	7.8/2	78.75	2.00	2.0

TABLE 27

PARTICLE SIZE DISTRIBUTION OF POSTSHOT AND PRE-PLUS-POSTSHOT DUST IN DESIGNATED SHELTERS[28]

Particle Size in Microns	Particle Size Distribution in Per Cent for Designated Shelters											
	RAa-8008		CAb-8012		RAd-8013		RCb-8015		Totals: Number		Totals: Per Cent	
	E	C	E	C	E	C	E	C	E	C	E	C
<0.5 (A)	0	0	0	0	0	0	0	0	0	0	0	0
0.5 - 1.9 (B)	0	3	0	0	40	0	75	0	115	3	29	1
2 - 5.9 (C)	36	30	44	0	0	0	10	20	90	50	22	12
6 - 10 (D)	6	26	6	30	10	70	10	30	32	156	8	39
>10 (E)	58	41	50	70	50	30	5	50	163	191	41	48
Totals	100	100	100	100	100	100	100	100	400	400	100	100



Particle Size Group — See Above

Figure 70

III. TENTATIVE BIOLOGICAL CRITERIA FOR ESTIMATING BLAST HAZARDS

As noted in the introduction, a beginning has been made in formulating tentative biological criteria for estimating human hazards associated with exposure to blast phenomena.[2, 11-14, 29, 30, 31] These will be summarized below.

A. Primary Effects (Pressure)

It is now known that mammalian tolerance to blast-induced variations in air pressure, as far as lethality and effects on the lungs are concerned, is dependent upon the rate, magnitude, character and duration of the pressure rise and fall, the size of the species of interest and probably the ambient pressure at which exposure occurs.[2, 4, 13, 17, 29-38] Too, it is clear that for major effects, biological tolerance to atypical or disturbed wave forms is different than it is for pulses of classical or near-classical configuration.[2, 4, 13, 29-32, 39-42] The latter will be discussed first.

1. Classical or Near-Classical Wave Forms

For a given species of mammal, the response of the thoraco-abdominal system to "fast"-rising overpressures is determined both by the magnitude and duration of the pulse.[2, 4, 13, 17, 29-39, 41, 42] Tentative estimates applicable to human adults are available for "long"-duration waves; viz., for explosive yields down to at least 1 kt. These are summarized in Table 28.[2, 4, 5, 11-14, 31, 43-45] The first column of numbers in Table 28 refers to maximum effective pressures measured at or near a biological target. The last column gives the incident overpressures from which these may occur if pressure reflects maximally.

Neither the effects of rise time and pulse duration, as they might influence the pressure tolerance of the eardrum nor the effects of age on blast tolerance has been systematically studied thus far, but a few data are available indicating that young rats are more susceptible than adults of the same species.[44] To the contrary, a systematic investigation of the role played by ambient pressure in blast tolerance has been under

TABLE 28

TENTATIVE CRITERIA FOR PRIMARY BLAST EFFECTS IN ADULTS APPLICABLE TO "FAST"-RISING, "LONG"-DURATION OVERPRESSURES IN AIR

(Modified from References 11, 14, 31)

Critical Organ or Event	Related Maximum Overpressure, psi: Maximum Effective at Target	Related Maximum Overpressure, psi: Incident with Maximum Reflection
Eardrum Failure*		
Threshold	5	2.3
50 per cent	15 - 20	6.2 - 8.0
Lung Damage+	12 – 15	
Threshold	10 - 12	4.4 - 5.1
Lethality†		
Threshold	30 - 42	11 - 15
50 per cent	42 - 57	15 - 18
Near 100 per cent	57 - 80	19 - 24

*Data from Zalewski,[43] WT-1179,[4] WT-1467,[5] Richmond[44]
+Data from Richmond,[44] Pratt et al.[45]
†Data from CEX-58.8,[12] DASA 1341,[11] CEX-63.7,[2] DASA 1335[13]

NOTE: The lung and lethality data, derived using shock tubes in Albuquerque at 12 psi using a side-on exposure geometry against a reflecting surface, apply strictly to such conditions wherein the maximal reflected pressure was the maximal effective pressure. There may be enough evidence soon to scale the data to sea level (see text) and to other geometries of exposure.

way for some time.[46, 47] To date, one exploratory study using mice indicates that tolerance to overpressure is indeed a function of the ambient pressure at which exposure occurs.[47] If work with other species continues to support the same conclusion, then biological scaling to obtain figures applicable for exposure at different altitudes will become feasible. If it does, this probably means that the lung and lethality data in Table 28, derived at Albuquerque altitude, can be scaled to sea level using the factor 1.2 which is the ratio of sea-level pressure (14.7 psi) to the ambient at Albuquerque (12 psi).

Also regarding the lung and lethality data in Table 28, it is important to realize that they were derived using many hundreds of animals all exposed side-on against an end plate closing an instrumented shock tube. In each instance therefore, the effective maximum pressure was the reflected pressure. This pressure was applied almost instantaneously to the side of the animal mounted against the shock-tube end plate, but occurred in two steps on the upstream side of the animal; viz., the incident followed a very short time later by the reflected pulse passing back over the animal from the end plate of the tube.

Work is under way to learn how to scale the shock-tube data to other exposure geometries such as side-on and end-on to the advancing pulse in the open — as well as the various angles in between — and prone on the ground with the source of the blast varying on an arc from immediately overhead down to the surface of the ground.

2. Disturbed Wave Forms

a. Stepwise Increases in Overpressure

For certain locations of exposure, such as varying distances away from reflecting surfaces, stepwise increases in overpressure can occur.[2-5, 11-14, 30-32, 39-42] This can involve the initial application of the incident followed by the reflected pulse.[13, 32, 39-42] If the interval between the incident and reflected pressures is very short — perhaps like 0.1 to 0.4 msec for small animals[13, 32, 39, 40] and 0.5 to 1.0 msec for the dog[13] — the animal "appreciates" the pressure rise as one pulse. For longer intervals of time, perhaps a few msec for animals as large as man, the

biologic target "sees" the pressure as two separate pulses. As a consequence, tolerance rises by a factor of about 1.6 for the guinea pig[2, 13, 32] and may be as much as a factor of 2 for large animals including the human case.

Unfortunately, it will not be possible to make a more precise statement until studies of stepwise increases in overpressure are extended to the larger and more of the smaller mammalian species.

b. Other Wave Forms

If the rising phase of a pressure pulse increases smoothly or in small, incremental steps, it is known that the tolerance of mammals to overpressure increases by factors of from 3 to 5 providing the very early phase of the increase in pressure is not great and fast enough to be lethal in its own right.[2, 48, 49] Again, the lack of data does not allow tolerance to be more fully defined. However, it is known that mammals weighing about 35 - 40 lbs and exhibiting 50-per cent lethality at a P_{max} of 50 psi if the wave is "fast" rising and of "long" duration, will tolerate well over 200 psi if the pulse increases to a maximum in 20 or more msec.[2, 48, 49]

B. Secondary Effects (Missiles)

A variety of materials may be energized by blast overpressures, winds, ground shock and gravity. Even if they should strike man as missiles, they might or might not be hazardous depending upon several exigencies: i.e., the kind, character, mass and velocity of the missile; the angle at impact; whether or not penetration or perforation occurred; and the area and organ of the body involved. Though the situation is fraught with complexities and any biological criteria to help assess possible hazards from blast-induced debris are likely for some time to be incomplete and inadequate, some that are tentatively useful have nonetheless been formulated using data from several sources.[2, 12, 50-54]

In these, reproduced in Table 29,[11, 14, 31] 10-gram window-glass fragments were employed as an example of a penetrating missile, and the nonpenetrating hazard was exemplified using a 10-pound object assumed to

TABLE 29

TENTATIVE CRITERIA FOR SECONDARY BLAST EFFECTS

(Modified from References 11, 14, 31)

Kind of Missile	Critical Organ or Event	Related Impact Velocity ft/sec
Nonpenetrating 10-lb object	Cerebral Concussion:*	
	Mostly "safe"	10
	Threshold	15
	Skull Fracture:*	
	Mostly "safe"	10
	Threshold	15
	Near 100 per cent	23
Penetrating 10-gm glass fragments	Skin Laceration:+	
	Threshold	50
	Serious Wounds:+	
	Threshold	100
	50 per cent	180
	Near 100 per cent	300

*Data from Lissner and Evans;[52] Zuckerman and Black;[53] Gurdjian, Webster and Lissner[54]

+Data from AECU-3350[51] and WT-1470;[50] figures represent impact velocities with unclothed skin.

strike the head, the latter being regarded as the critical organ for minimal hazard. That the liver and spleen, as well as other abdominal organs and even the eye, may be more susceptible to accelerative impact loading than the head has been recognized.[2, 11, 14] However, the lack of relevant quantitative data currently precludes regarding them as more critical organs than the head.

C. Tertiary Effects (Whole-Body Displacement)

In addition to translational phenomena involving penetrating and nonpenetrating missiles, whole body displacement and the accelerative and decelerative experiences related thereto that are induced by blast pressure, winds, ground shock and gravity, represent one of the major, and under certain circumstances, the most far-reaching effects of blast on man.[11, 12, 14, 29-31, 55, 56] Whether or not the effect is of consequence depends upon a variety of factors. Among them are the magnitudes of the forces involved; the time, distance and angle over which they are applied; the character of the contact surface concerned; and the area of the body traumatized.

Mostly for the sake of simplicity, but also because it is difficult to know which portions of the body to relate to acceleration-time data, tentative tertiary blast criteria were developed on the basis of impact velocity. These are shown in Table 30. They were assembled using data for skull fractures;[54] information on whole body impact derived from an intraspecies study of small animals;[57] figures for foot, ankle and leg fractures;[53,57-59] and work with human volunteers subjected to impact loads in the seated and standing positions.[60-62]

Even though the data are crude and incomplete, the criteria are helpful in assessing not only the various levels of decelerative injury that may follow translation, but in evaluating some of the possible hazards from accelerative loading that can occur in shelters responding to ground shock. In either case, the sharply challenging loads are likely to be of "short" duration when collision with a hard object occurs, mainly because the stopping time and distance are a function mostly of the cushioning effects of the body tissues themselves.

TABLE 30

TENTATIVE CRITERIA FOR TERTIARY BLAST EFFECTS

(Modified from References 11, 14, 31)

Condition Critical Organ or Event	Related Impact Velocity ft/sec
Standing Stiff-legged Impact*	
Mostly "safe"	
No significant effect	<8 (?)
Severe discomfort	8 - 10
Injury	
Threshold	10 - 12
Fracture threshold (heels, feet and legs)	13 - 16
Seated Impact*	
Mostly "safe"	
No effect	<8 (?)
Severe discomfort	8 - 14
Injury	
Threshold	15 - 26
Skull Fracture+	
Mostly "safe"	10
Threshold	13
50 per cent	18
Near 100 per cent	23
Total Body Impact†	
Mostly "safe"	10
Lethality threshold	20
Lethality 50 per cent	26
Lethality near 100 per cent	30

*Data from Draeger, Barr, Dunbar, Sager, Shelesnyak;[58] Black, Christopherson and Zuckerman;[59] Swearingen, McFadden, Garner and Blethrow;[60] Hirsch[61] and Eiband.[62]

+Data from Gurdjian, Webster and Lissner;[54] Zuckerman and Black.[53]

†Data from DASA 1245.[57]

This factor and the concept of iso-velocity values, being the physical parameter with which one might relate biological response, was given considerable meaning by a perceptive and much more refined analytical contribution recently published by Hirsch.[61] Figure 71, in which Figures 7 and 8 are reproduced from his work set forth in a David Taylor Model Basin report,[61] shows estimated iso-velocity asymptotes as criteria for impact tolerance in standing and seated positions.

The horizontal iso-velocity lines at 10 ft per second for the stiff-legged standing man, and at 15 ft per second for the seated man, apply (as the illustrations show) to the "high"-G, but "short"-duration loads. The msec-duration figures in the charts refer to the time the average G must act to give the velocity-acceleration-time-relationships shown.

The vertical iso-acceleration lines define tolerance when the acceleration pulse is constant and prolonged; viz., since it is reported that 1500 lbs applied statically produced fracture in one leg and therefore 3000 lbs will be required if one is standing stiff-legged on both feet, 20 G applied to a 150-lb man can be expected to be near the fracture level, a fact noted in the upper illustration of Figure 71 by the vertical portion of the shaded area which was drawn parallel with the 20 G line.

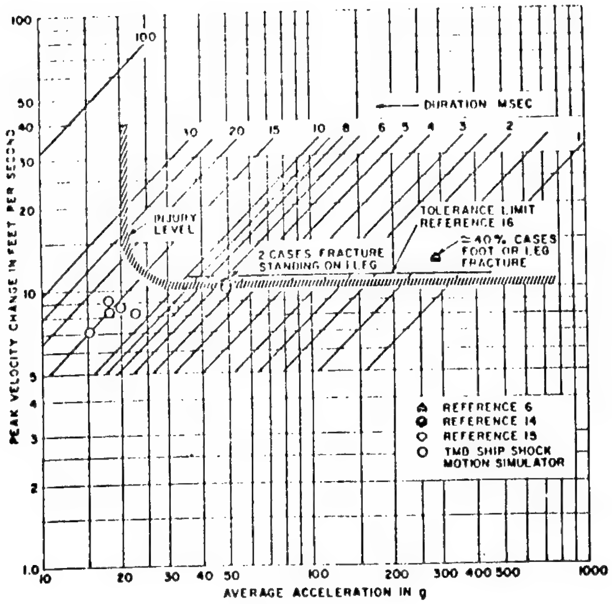
The lower illustration in Figure 71 contains 3 "low"-acceleration asymptotes. One refers to the design limit for ejection seats and the other two (the heavily shaded area and the dotted line), according to Hirsch,[61] span the tolerance values ranging from 15 to 28 G given in the literature for the tolerance limit of the spine to fairly static loads.

D. Miscellaneous Effects

1. Non-Line-of-Site Thermal Hazards

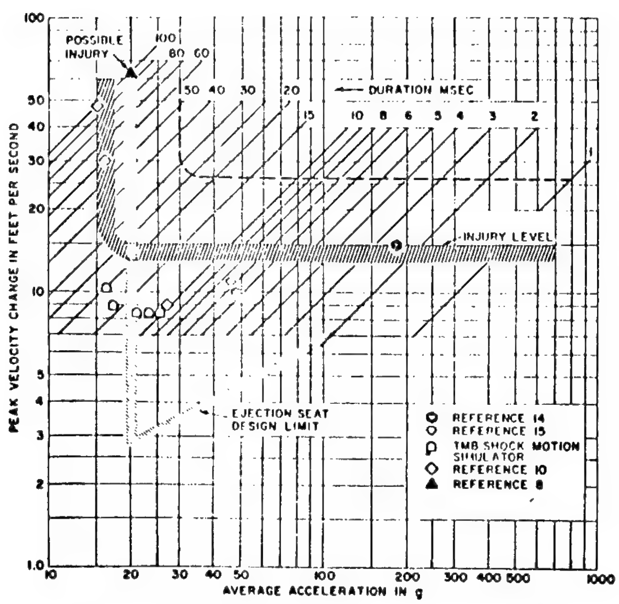
Hot, Debris-Laden Gases

Apparently the thermal biology literature contains no laboratory data relevant to the exposure of animal or human skin to



Tolerance of stiff-legged standing men to shock motion of short duration 61

For references numbered 6, 8, 10, 14 and 15 above and below see bibliography items 58, 63, 64, 65 and 66, respectively.



Tolerance of seated men to shock motion of short duration 61

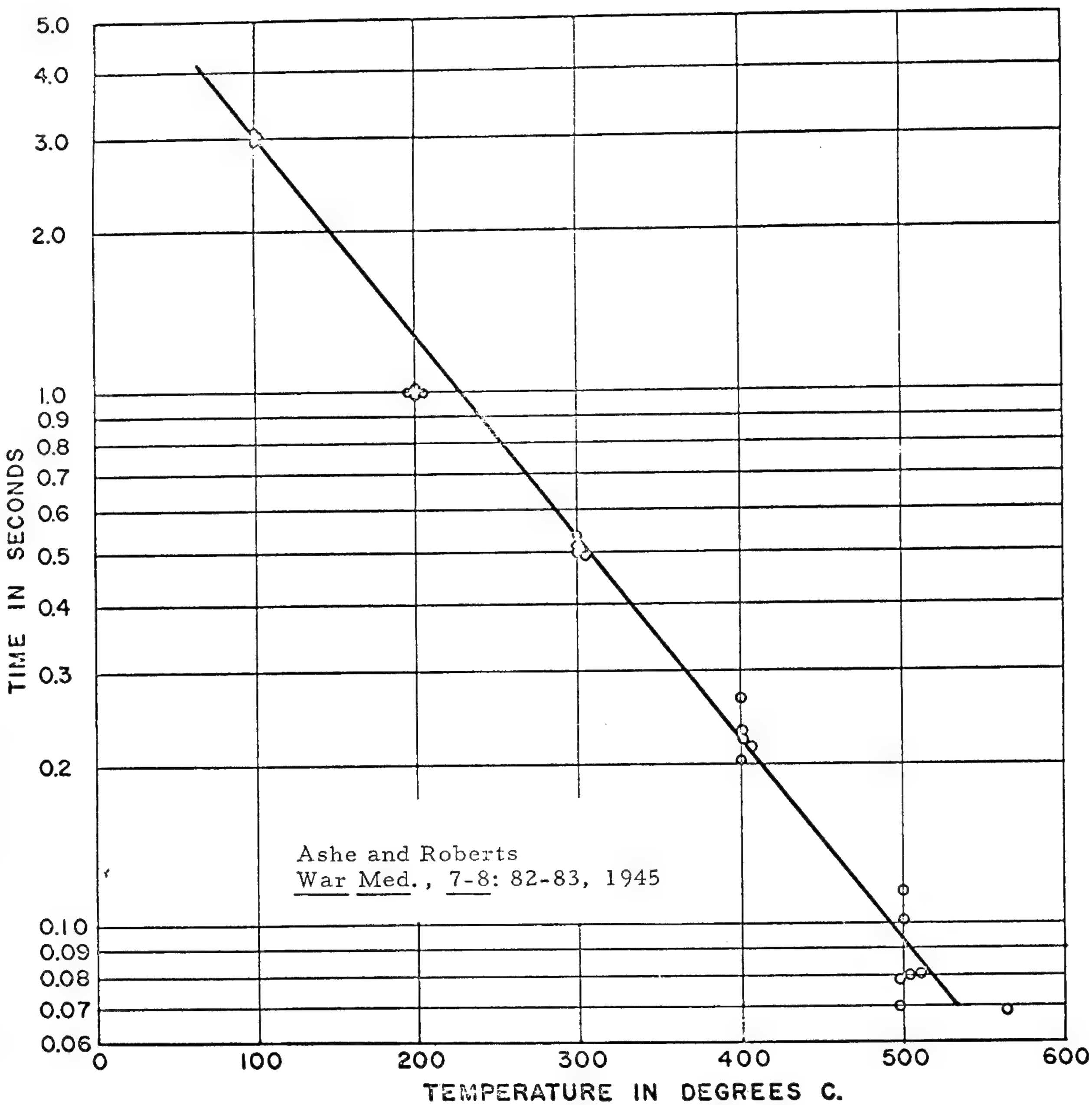
Figure 71

moving hot, dust-laden air. Also, experimental information about burns produced by hot, moving gases, when the exposure time is measured in a few fractions of a second, seems to be sparse indeed. Accordingly, it is not possible to formulate biological criteria that are germane to the conditions under which non-line-of-site thermal burns were noted in the "open" shelters at the Nevada Test Site; viz., hot, dust-laden air, moving at high velocity over biological targets for time periods ranging from about 75 - 120 msec, the "fill-time" of the shelters. These intervals represent the time it took for the inside shelter pressures to become equal to the outside pressures due to the positive winds moving into the structure with the blast wave.

However, data shown in Figures 72 and 73, from a study by Ashe and Roberts[67] involving the exposure of human volunteers to air of various temperatures blown at 6 liters per minute through a tube 1 cm in diameter, have some relevance to thermal hazards when calories are delivered to the skin mostly by the process of convection. Figure 72 shows the temperature-time relationships found to be associated with a minimal thermal insult to the skin; namely, the occurrence of an initial erythema (redness) within 15 minutes, which however disappeared within 24 hours.

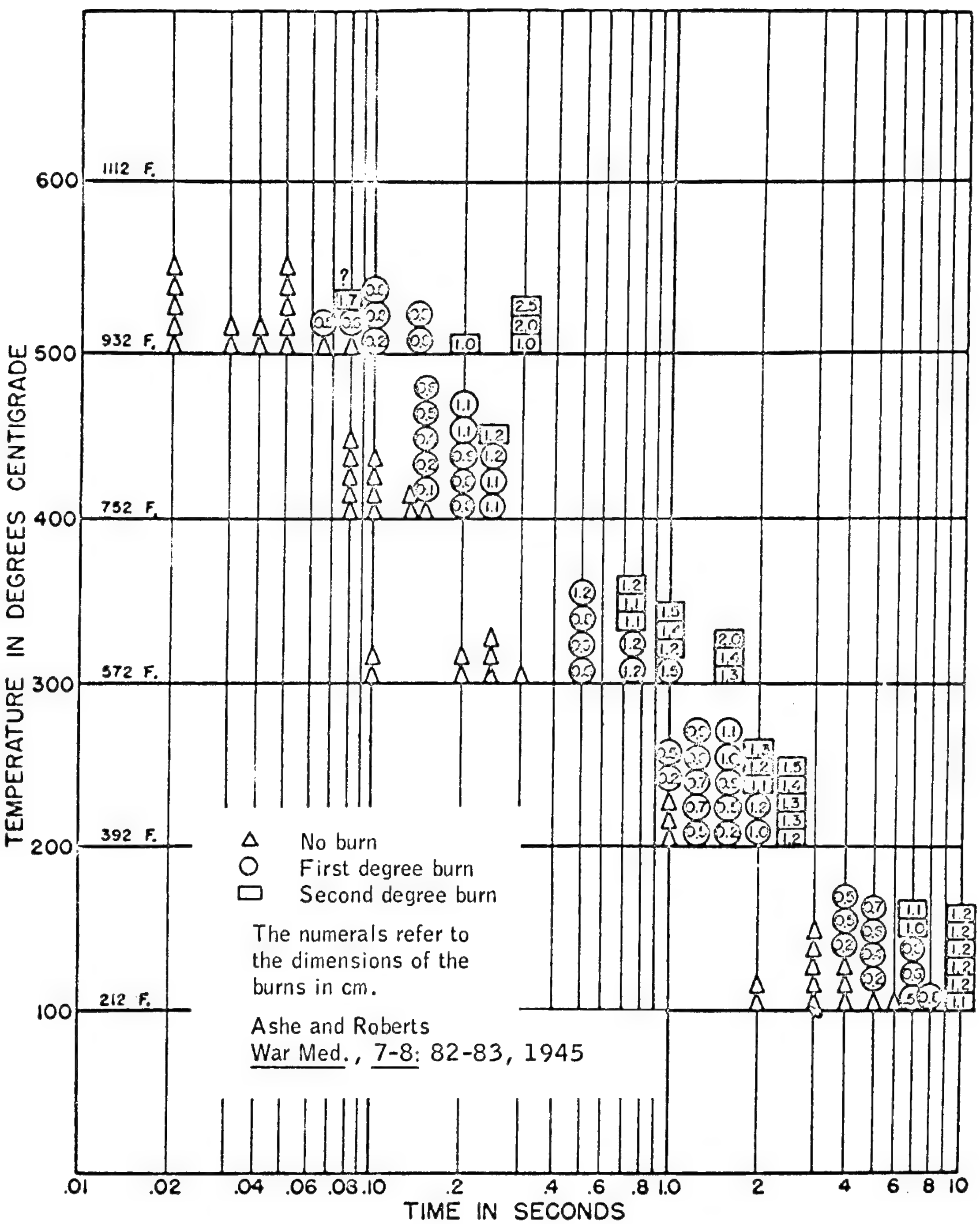
Figure 73, in addition, shows the temperature-time conditions necessary to produce the indicated burns on the forearms of 5 volunteers, each undergoing 5 exposures at temperatures of 100, 200, 300, 400 and 500°C. It is of interest to point out that Ashe and Roberts regarded a burn showing erythema for longer than 24 hours, but without vesiculation, as a first degree burn. Second degree injuries were defined as blistering burns. The vesicals noted varied from 0.5 to 1.0 cm in diameter. They were accompanied by a surrounding erythematous area from 0.8 to 2.0 cm in diameter.

It should be emphasized that the data in Figures 72 and 73, shown here mostly because they do involve exposure times ranging from a few seconds down to a few tens of msec, apply to low velocity air that contains no materials that might significantly increase the thermal capacity of the moving gas. Therefore, the curves in Figures 72 and 73 needs be



Time-temperature relationship required to produce erythema without a burn[67]

Figure 72



Temperature-time relationship producing indicated degree of hot-air burns of human skin[67]

Figure 73

regarded as useful for orientation only, and not to help interpret thermal events that occurred in the Nevada shelters and were associated with exposure to very high velocity air carrying considerable quantities of quite hot dust into the structures.

Compression Heating

It may serve some purpose here to point out that experience with shock tubes clearly show that mammalian lethality occurs well below pressures associated with temperatures high enough to burn animals. Occasionally, at pressures near the upper portion of the lethality curve, minimal singeing of the vibrissa and the fur of animals has been observed.[44]

Other Blast-Induced Thermal Hazards

Blast-induced fires and burns from sizable pieces of hot debris are known to occur. Those interested in temperature-time criteria for hazards from flames, radiant surfaces and hot circumambinet air and for hot objects are referred to the work of Henriques;[68] Henriques and Moritz;[69] Moritz;[70] Moritz and Henriques;[71] Moritz, Henriques, Dutra and Weisiger;[72] Büttner[73] and others including the many contributors to the recent text edited by Hardy.[74]

2. Dust Inhalation

Whether or not the inhalation of dust and other aerosols, radioactive or not, can be hazardous to man poses a number of complex questions to which only the future holds firm answers. Among the factors involved are the following: the physical and chemical properties of the inhaled material; the concentration actually inhaled; the particle size, shape and density; the respiratory rate and volume; the relative amount of nasal versus mouth breathing; the time of exposure; the amount and location of the inhaled material initially deposited in the airways; the subsequent fate and residence time of the materials in the body; and for insoluble particulates, perhaps soluble aerosols also, the ciliary clearance time under conditions of continuous exposure may be quite important indeed.

Lung Deposition

Figure 74, reproduced from a report of the Subcommittee on Inhalation Hazards* chaired by H. A. Kornberg,[75] is helpful in that it summarizes the results of many estimates of per cent deposition in the lower and total respiratory tract as this varies with particle size and respiratory rate. Findeisen,[76] and Abramson[77] noting some of Findeisen's data, estimated that 10 - 30 micron particles are deposited as low as the terminal bronchioles of the lungs while those >30 microns are deposited only in the trachea, larynx, pharynx and the nasal passages and sinuses. Also, much of the inhaled material is swallowed including that which is swept into the throat by ciliary action in the tracheo-bronchial tree.

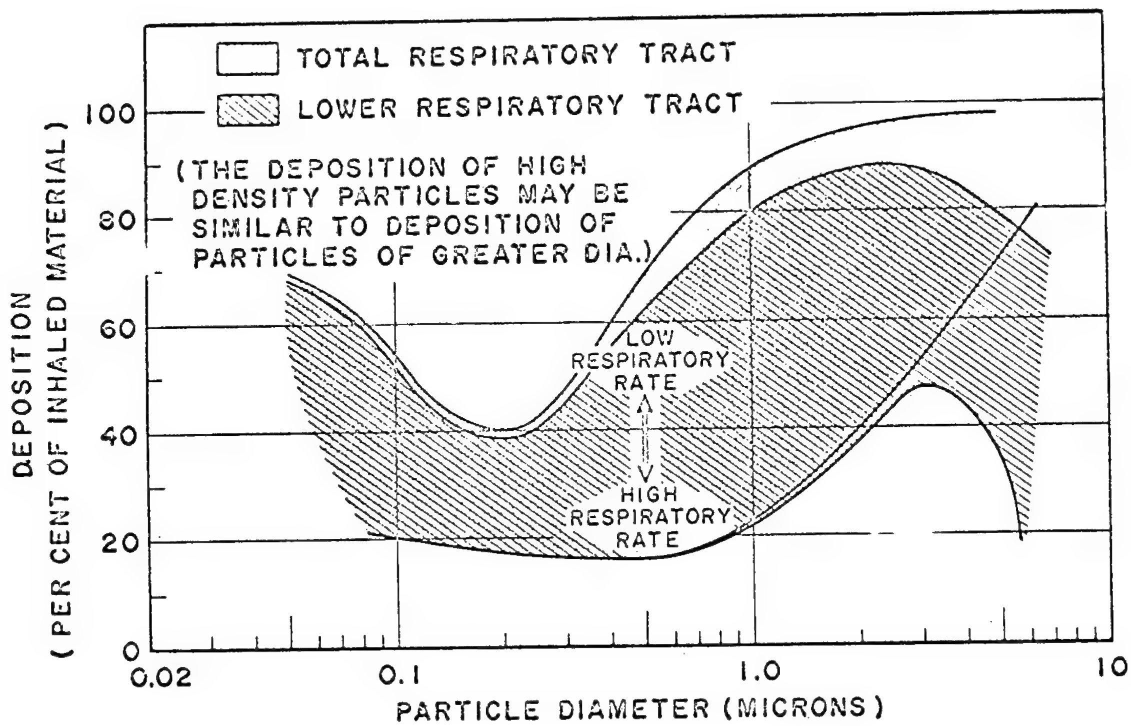
Figure 74 shows the marked variability, from about 20 to near 90 per cent, in the amount of inhaled material that is deposited, depending upon particle size as well as respiratory rate. For particles 1 micron in diameter, the deposition percentage may vary by a factor of 4 (from 20 to 80 per cent) due only to changes in respiratory rate. To produce a similar variation in deposition at constant respiratory rates, a change in particle size by a factor of near 10 is required — from around 0.5 to 5 microns.

Since the weight of a given particle is proportional to the cube of the radius, the dose or amount of material deposited in the lung is mostly associated with particle sizes above 0.5 microns. Particles smaller than this are probably significant only for very toxic material and perhaps only for very prolonged exposures.

Inert Dusts — Dust Asphyxia

Inert dusts or particulates of low solubility and toxicity may be hazardous simply because deposition in the lower portions of the respiratory tree is sufficient to mechanically occlude the airways and produce suffocation.[24] Desaga called attention to this problem, reported

*Of the Committee on Pathological Effects of Atomic Radiation, Dr. Shields Warren, Chairman.



Deposition in Respiratory Tract.
Reproduced from NAS-NRC Publication 848.[75]

Figure 74

relevant experiments using dogs and computed the amount of dust required to produce suffocation in adults to be about 30 cc: i.e., 30 gm for a unit-density material; 45 gm for a dust having a specific gravity of 1.5 (fly ash from soot traps in the coal operated Klingenberg power plant in Berlin and similar to plaster dust and dust developing in reinforced concrete* bunkers[24]); 75 gm for material having a density of 2.5 gm/cm^3 (that of reinforced concrete itself).

Using any of the applicable values noted above along with appropriate parameters, order-of-magnitude calculations can be made of the time it might take to produce dust asphyxia for a variety of conditions. As an example, Table 31 was prepared assuming the following conditions:

a. Density of the inhaled dust, 1.5 gm/cc.

b. Lung retention to be 50 per cent by weight of material inhaled.

c. Lung retention of 45 gm sufficient for asphyxia.

d. Respiratory volumes to be 10 and 90 liters per minute, these values being approximate for sitting at rest and a maximal work effort, respectively.

e. The concentration of inhaled materials ranged from 5 to 100 gm/m^3, but remained constant for each exposure.

Table 31 shows suffocation of an individual, breathing 10 liters per minute and inhaling dust having a concentration of 50 and 100 gm/m^3, might occur in 180 and 90 minutes, respectively. If, however, the ventilation rates were near the maximal (90 liters per minute), then asphyxia could ensue in 10 minutes for the higher and in 20 minutes for the lower dust concentrations. The figures of 50 and 100 gm/m^3 are interesting for at least two reasons; namely, first, dust concentrations

*Cement has a density of 0.82 - 1.95 and silica a density of 2.66 (Handbook of Chemistry, 9th Edition, Edited by Lang).

TABLE 31

COMPUTED ORDER OF MAGNITUDE-TIME-CONCENTRATION RELATIONSHIP TO PRODUCE DUST ASPHYXIA*

Dust Concentration		Amount Inhaled in mg/min		Amount Deposited in mg/min		Time to Deposit 45 gm in Minutes	
gm/m^3	mg/liter	10 lpm	90 lpm	10 lpm	90 lpm	10 lpm	90 lpm
100	100	1000	9000	500	4500	90	10
50	50	500	4500	250	2250	180	20
25+	25	250	2250	125	1125	360	40
10	10	100	900	50	450	450	50
5	5	50	450	25	225	900	100

*Assumed dust density was 1.5 gm/cc, 50 per cent of the inhaled material by weight was retained and 45 gm deposited in the lung would produce asphyxia.

+Nonhazardous in 1 hr for dogs exposed to Klingenberg dust (1.5 gm/cc) apparently because ciliary action mostly kept the deeper reaches of the lung free of particulates.

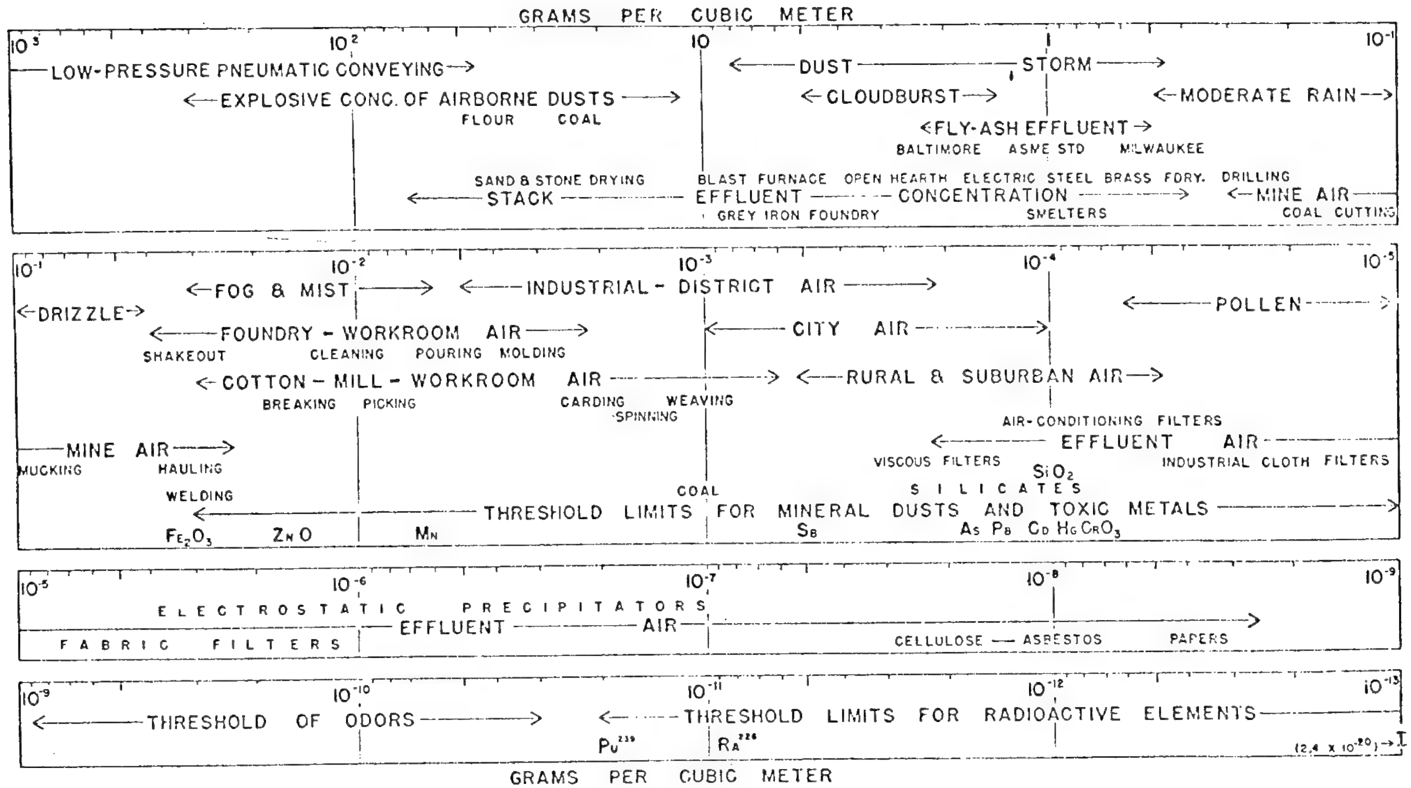
of 31.8 and 88 gm/m^3 were reported by Desaga[24] as found in two compartments of a reinforced concrete bunker of the Maginot Line following the experimental detonation of "H" charges (magnetic antitank hollow charges). Second, a dog inhaling in a chamber containing 80 gm/m^3 of Klingenberg dust was essentially asphyxiated in one hour.[24]

Also, it is probably significant that Desaga reported a dog inhaling 25 gm/m^3 of Klingenberg dust for 60 minutes showed no change in respiration within 30 minutes, was panting and coughing at the end of the exposure and slimy dust sediment was found only in the upper one-third of the trachea. Some dust was discernable in the alveoli. Apparently ciliary action served to clear the lung at a rate that was nearly equal to the deposition rate of particles. Thus, the 25 gm/m^3 concentration probably is a marginal concentration for the dog and perhaps so for man. Desaga personally inhaled this concentration of Klingenberg dust for 0.5 minutes (16 deep inspirations) and reported coughing, copious nasal secretion and mild conjunctivitis as long as 6 hours after the exposure.

Toxic-Particulates and Aerosols

No attempt will be made here to deal with the complex problems of moderately and highly toxic materials, including those that are radioactive and usually classed as internal emitters. Suffice it to say that serious technical difficulties are involved, that much relevant research is under way and that many more data are required before it will be possible to formulate meaningful biomedical criteria for animals and man.[75] Also it is helpful for orientation purposes to study the useful illustration, compiled in 1952 by First and Drinker[78] and reproduced here as Figure 75.

A study of the figure shows that toxicity for radioactive elements, being in the range of about 10^{-11} to 10^{-20} gm/m^3 is many orders of magnitude separated from the concentrations of dust occurring in storms which range from about 0.5 to 10 gm/m^3. Thus the dust concentration in the shelters in Nevada being from 2 to 5.5 gm/m^3 (see Table 26), were comparable to those seen in severe dust storms. They pose no hazard as far as suffocation is concerned, but might be other than annoying and irritating, depending upon the chemical nature of the



Chart, plotted on logarithmic scale, showing atmospheric conditions dealt with in practice.

Reproduced from First and Drinker, Arch. Indus. Hyg. Occup. Med., 5: 387, 1952 [78]

Figure 75

particulates. Should these be silicates — and there are bound to be some from the sand and aggregates used in the concrete — then Figure 75 shows that around 10^{-4} gm/m^3 has proven a troublesome range in industry.

Finally, it is well to say that the settling rates of the various sized particulates in a shelter can be a significant factor in determining the particle size of material inhaled as well as the dust concentration. This follows because as sedimentation proceeds, the spectrum of concentration and particle sizes passing the face of an individual will vary. One result is that the time of initial exposure will be a function of settling velocity and the time of subsequent exposure, among other things, will be a function of the level of postshot activity in the shelter producing resuspension of the dust that was previously deposited on the floor.

IV. SUPPORTING DATA

The tentative biomedical criteria set forth above were based on a variety of information drawn from the literature and from ongoing programs in environmental medicine. In some instances, extrapolations from a few as well as many animal data were employed. In others, the "best-estimate" or "order-of-magnitude" approach was followed if relevant data were incomplete, meager or absent entirely. Also, whenever available, all possible use was made of human experience thought appropriate.

Thus, those who would assess the hazards of blast-induced variations in man's environment are currently confronted by uncertainties that are closely allied to the "state of the art" in many areas. An attempt will be made below to elaborate this concept by citing selected data that help elucidate the nature and kind of the many problems involved, that bear upon the validity of the tentative criteria available and that indicate the directions in which future research needs be directed if blast-related hazards are to be assessed more precisely.

A. Primary Blast Effects

1. Eardrum

The eardrum may rupture if either over or underpressures

of sufficient magnitude are applied externally to the ear.* Only over-pressure data were considered in formulating the criteria noted in Table 28. The most applicable data are those obtained in 1906 by Zalewski[43] using fresh human cadavers. Pressure, applied through a tube sealed in the external auditory meatus, was increased until the eardrum ruptured. Zalewski's results,[43] reproduced from a compilation published in WT-1179[4] according to age and sex, are set forth in Table 32. The grouped data show a trend with age, the average pressures for rupture being about 33 psi in subjects 1 - 10 years of age; these decrease to between 18 and 20 psi for the groups above 30 years of age. Variations in the data were considerable, and the lowest overpressure rupturing a normal drum was reported to be 5.4 psi.

Zalewski used a similar technique on 10 dogs (age not stated) and reported the average pressure required to rupture the ear-drum was about 15 psi.

Richmond et al.[5] summarized experience with dog eardrums in the 1953, 1955 and 1957 Nevada shelters. The data, redrawn as the lower right-hand curve in Figure 76, shows the P_{50}+ to be about 31 psi. All the animals were young adults and it is of interest that this figure of 31 psi is close to the average figure of 33 psi observed for the first decade age group by Zalewski (see Table 32).

An effort was made by White et al.[4] to assess the role of the maximum pressure, the rate of pressure rise, the pressure ratio and the fractional pressure differential in eardrum rupture. Data were insufficient to conclude other than that the maximum pressure was as good a physical parameter as any with which to associate eardrum failure. There was, however, a suggestion that the tympanic membrane was "frequency sensitive." Of course, if this were true, the rate of pressure rise might well be a factor as well as the relation of the time

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*For a brief review of quantitative data, see WT-1179.[4]

+The pressure associated with 50 per cent failure of the eardrum.

TABLE 32

PRESSURES APPLIED TO EXTERNAL AUDITORY MEATUS REQUIRED TO RUPTURE TYMPANIC MEMBRANES OF FRESH CADAVERS*

Type of cadavers	No. of cases	Age, years	Pressures required to rupture tympanic membranes of cadavers: Minimum, Cm Hg	Minimum, Psi	Maximum, Cm Hg	Maximum, Psi	Mean, Cm Hg	Mean, Psi
Human male	10	1–10	108	20.9	223	43.2	172.3	33.3
	8	11–20	43	8.3	163	31.5	121.2	23.4
	6	21–30	92	17.8	135	26.1	111.3	21.5
	12	31–40	33	6.4	153	29.6	99.0	19.1
	5	41–50	93	18.0	113	21.9	100.4	19.4
	6	51–60	85	16.4	198	38.3	123.3	23.8
	7	61–70	55	10.6	163	31.5	90.9	17.6
	5	>70	98	19.0	137	26.5	113.8	22.0
Total	59					Average	118.8	23.0
Human female	9	1–10	125	24.2	212	41.0	170.2	32.9
	7	11–20	31	6.0	228	44.1	142.4	27.5
	9	21–30	79	15.3	123	23.8	101.0	19.5
	5	31–40	100	19.3	183	35.4	140.6	27.2
	6	41–50	87	16.8	163	31.5	113.3	21.9
	6	51–60	70	13.5	118	22.8	93.6	18.1
	7	61–70	28	5.4	133	25.7	103.3	20.0
	3	>70	84	16.2	118	22.8	99.6	19.3
Total	52					Average	123.1	23.8
Human male and female	19	1–10	108	20.9	223	43.2	171.2	33.1
	15	11–20	31	6.0	228	44.1	131.3	25.4
	15	21–30	79	15.3	153	29.6	105.2	20.3
	17	31–40	33	6.4	183	35.4	111.1	21.5
	11	41–50	87	16.8	163	31.5	107.5	20.8
	12	51–60	70	13.5	198	38.3	110.2	21.3
	14	61–70	28	5.4	163	31.5	97.1	18.8
	8	>70	84	16.2	137	26.5	108.5	21.0
Total	111					Average	120.9	23.4
Dogs	10		47	9.1	118	22.8	77.2	14.9

*Tabulated from the data of Zalewski.[43]

PRESSURE TOLERANCE OF DOG EARDRUM EXPOSED IN SHOCK TUBE AND NEVADA SHELTERS TO "FAST"- AND RELATIVELY "SLOW"-RISING OVERPRESSURES OF "LONG" DURATION

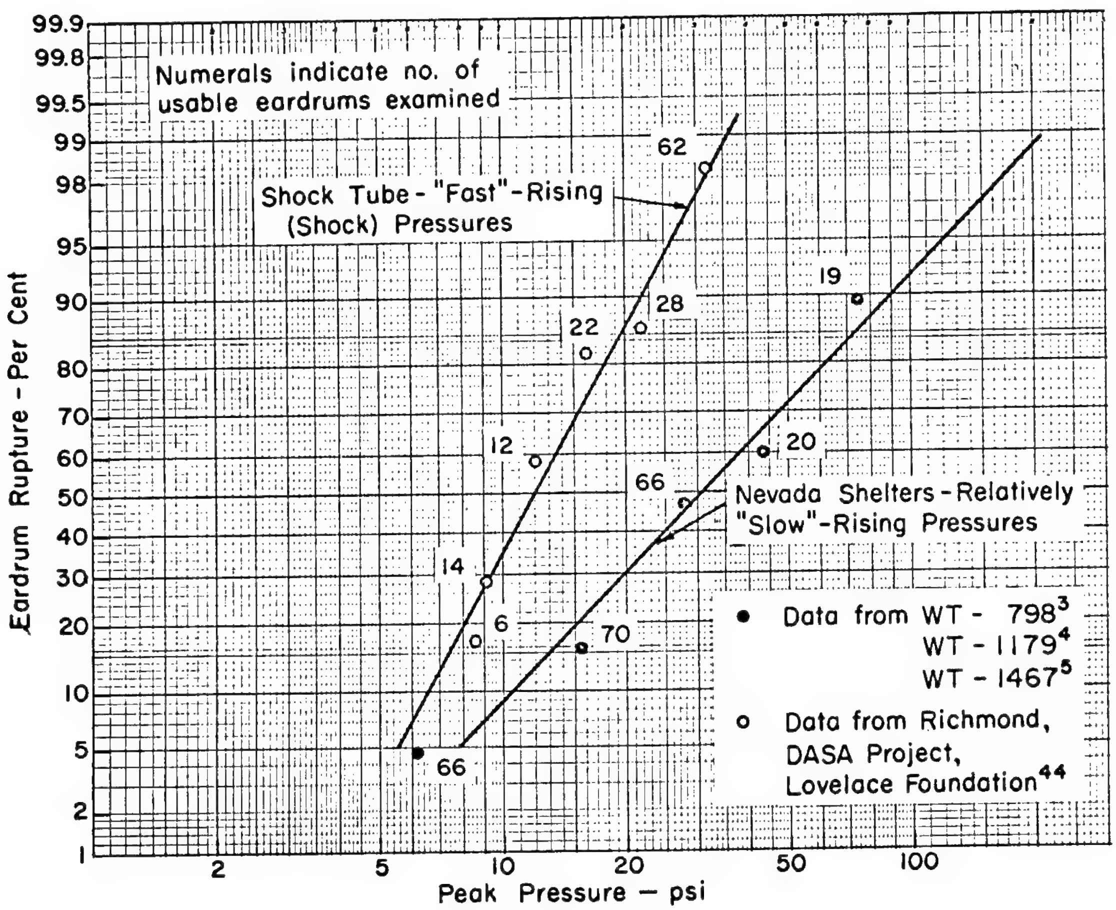


Figure 76

of application of pressure to the natural frequency of the membrane and the ossicles to which it is attached.

Though no systematic study of eardrum failure as a function of "fast"- or "slow"-rising overpressures in any mammal is known to the authors, a recent study of the threshold conditions for lung hemorrhage in dogs allowed Richmond[44] to assemble some data for "fast"-rising overpressures of "long" duration. The results are graphically portrayed in Figure 76 as the left-hand curve, which is an "eye-ball" fit to data tabulated in the top portions of Table 33 arbitrarily assembled on log-normal paper according to pressure groups. Though quite variable, the divergence between the two lines in Figure 76 suggests that on the average the dog's eardrum is more tolerant of "slowly" rising than of "fast"-rising overpressures of long duration; i.e., the P_{50} is near 31 for "slowly" and 12 psi for "fast"-rising overpressures.

To help illustrate the variability in the data, but also to emphasize the probable threshold value for eardrum rupture, Figure 77 was prepared on linear paper using the data tabulated in Table 33. The left-hand curve gives the shock-tube results while that on the right shows the shelter data. The ranges of pressure associated with each of the data groups are also noted for both curves. First, regarding the variability, Figure 77 shows 40, 50 and 60 per cent eardrum rupture on the average occurred between about 10 - 26, 12 - 31 and 14 - 39 psi, respectively, depending upon whether "slow"- or "fast"-rising pressures were involved. The hatched areas associated with each curve in Figure 77 serve to emphasize the variation in the P_{max} for each pressure group utilized to determine the percentage of failure of the tympanic membrane.

Second, with reference to the threshold values for drum failure in the dog, the data in both Figures 76 and 77 converge between the 4 and 5 psi range. In this regard, it is useful to point out that 4.6[4] and 4.1 psi[5] were the lowest overpressures known in Nevada to be associated with eardrum failure in dogs, values close to that of 5.4 psi for humans already mentioned as found by Zalewski.[43] Though lower pressures will probably rupture diseased and scarred human drums and various figures for the threshold are found in the literature (3.9 - 7.7 psi given by

TABLE 33

DOG EARDRUM TOLERANCE WHEN EXPOSED IN SHELTERS AND AGAINST THE END PLATE CLOSING A SHOCK TUBE TO "SLOW"- AND "FAST"-RISING OVERPRESSURES OF "LONG"-DURATION

Group or Operation	Maximum Pressure Psi		Number Ruptured/ Total Usable Drums	Percent Drums Ruptured
	Range	Average		
Shock Tube[44]	8.5-8.6	8.5	1/6	16.7
	8.7-9.5	9.1	4/14	28.6
	9.6-13.1	12.3	7/12	58.3
	13.2-19.3	16.2	18/22	81.8
	19.4-25.0	22.2	24/28	85.7
	25.1-38.4	31.7	61/62	98.3
Teapot[4]*	1.3	1.3	0/4	0
Teapot*	2.6	2.6	0/4	0
Teapot*	3.7	3.7	0/4	0
Plumbob[5]	4.1	4.1	1/4	25
Teapot	4.3	4.3	0/4	0
Teapot	4.6	4.6	1/4	25
Teapot	6.7	6.7	0/20	0
Upshot-Knothole[3]	7.5-8.5	8.0	1/24	4.2
Plumbob	9-10	9.5	0/10	0
Average	4.1-10	6.2	3/66	4.6
Upshot-Knothole	8-13	10.5	0/34	0
Teapot	11.5-13.5	12.5	0/4	0
Upshot-Knothole	12.5-16.0	14.3	1/16	6.3
Teapot	18.5	18.5	2/4	50.0
Teapot	21.4-22.8	22.0	8/12	66.6
Average	8-22.8	15.6	11/70	15.7
Upshot-Knothole	19.0-24.0	22.5	1/14	7.1
Plumbob	23.8-27.0	25.5	8/16	50
Plumbob	30.0-30.5	30.3	12/16	75
Teapot	26.6-36.9	33.8	10/20	50
Average	19.0-36.9	28.0	31/66	47.0
Upshot-Knothole	38	38.0	5/8	62.5
Teapot	38.6-43.1	40.9	2/4	50.0
Teapot	38.6-47.0	42.8	2/4	50.0
Teapot	53	53.0	3/4	75.0
Average	38-53	43.7	12/20	60.0
Teapot	63.6-73.2	66.6	10/12	83
Teapot	71.6	71.6	3/3	100
Teapot	85.5	85.5	4/4	100
Average	63.6-85.5	74.6	17/19	89.5

*Not used in averages for following group.

EARDRUM-FAILURE RELATIONSHIP SHOWING PRESSURE RANGE FOR EACH DATA GROUP

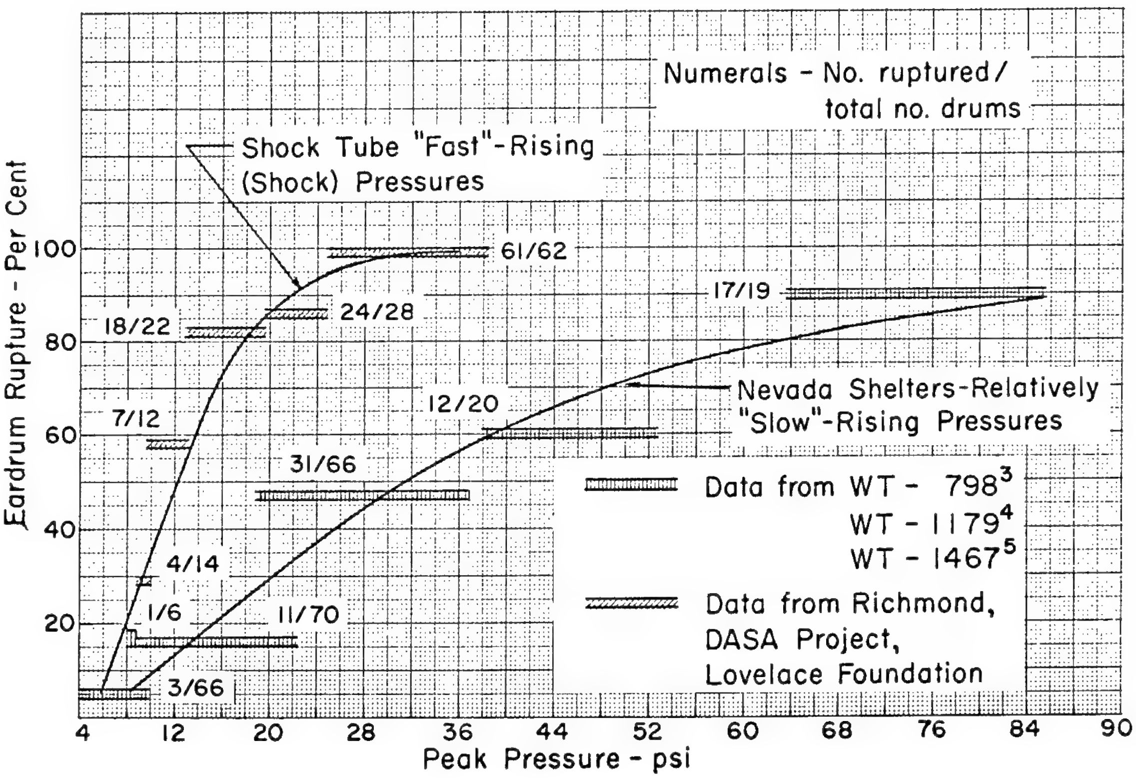


Figure 77

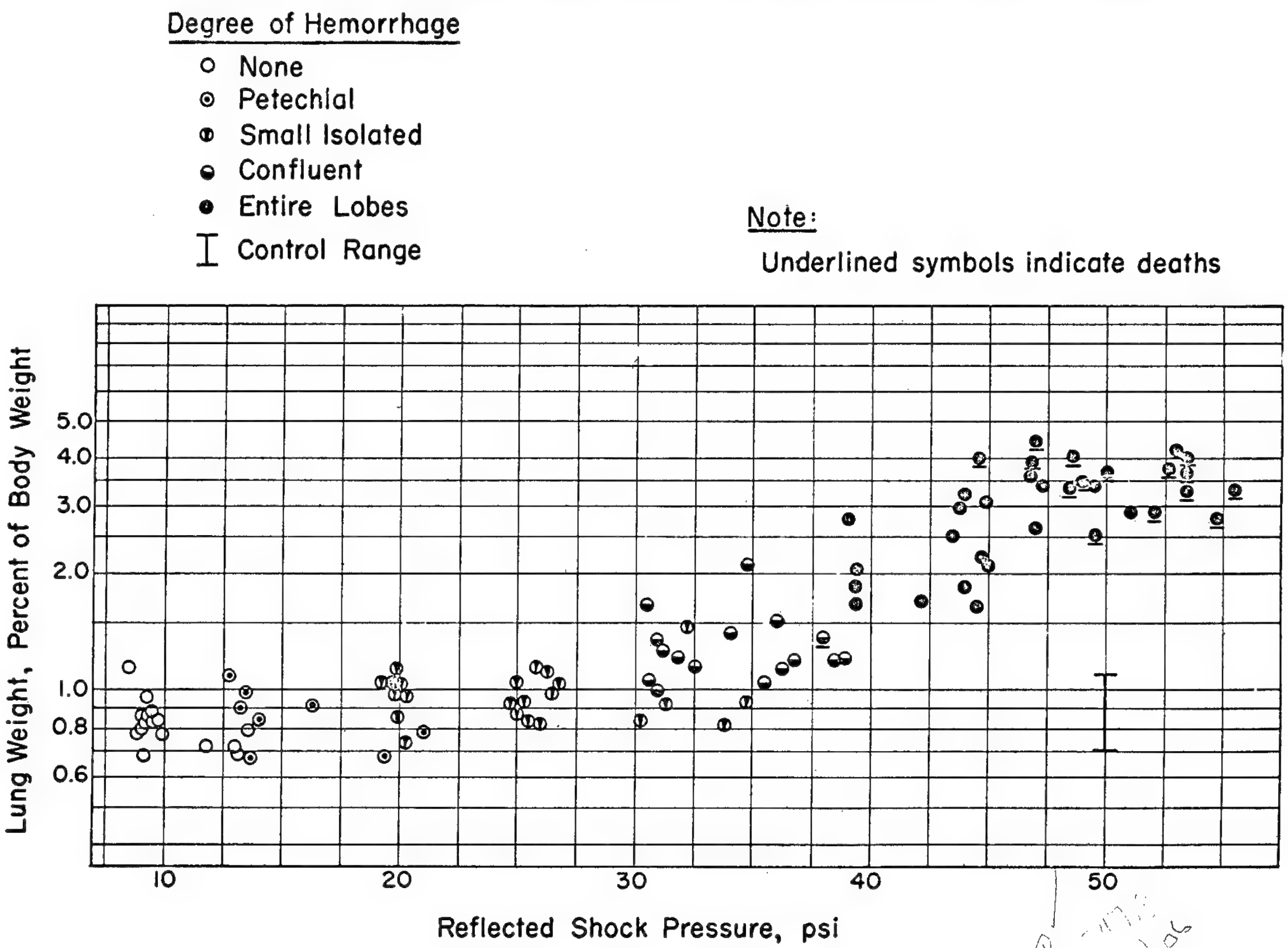
Perlman,[79] 7 psi by Corey,[80] 10.3 psi for normal and 5.9 psi for scarred drums by Shubert,[81] who regards 3.1 as the "safe" pressure), it would seem that a value near 5 psi is the best current estimate for both man and the dog.

2. Lung Injury Threshold

Up until recently, the estimate of the threshold overpressure that might produce grossly apparent lung damage in dogs was placed at 15 psi[2,11,12,14,29,31] on the basis of one dog exposure in Nevada at near 8 psi incident with a probable reflection to about 22 psi.[50] Recent work of Richmond,[44] summarized in Figure 78 to show lung-weight-overpressure relationship for dogs subjected side-on against the end plate of a shock tube to "fast"-rising, "long"-duration overpressures, has, however, made it clear that lung hemorrhage was grossly apparent in animals exposed to 12 psi overpressure. Since the data show no gross damage between 8 - 12 psi, the value of 10 - 12 psi was tentatively included in the human criteria, given in Table 28 above, as the probable threshold overpressure for damage to the human lung. These figures may be lowered subsequently, depending upon the results of microscopic studies of lung tissue now under way.

It is of interest here to call attention to Table 34 prepared to show the lung weight-overpressure relationship found in dogs exposed in 1957 inside Group Shelters 8001 and 8002.[5] It is apparent from Table 34, arranged in the order of increasing pressure of exposure, that overpressures of close to 30 psi were not associated with grossly apparent hemorrhage of the lung. This finding is in contrast with the data in Figure 78 for "fast"-rising overpressures which show that overpressures from 12 - 30 psi were invariably associated with grossly apparent lung hemorrhage. Thus, there is this small bit of evidence that, as is the case with lethality in dogs, the minimal overpressure of "long" duration that produces grossly apparent hemorrhages of the lungs is associated with a "fast"-rising pulse; viz., the animal will tolerate higher maximum pressures without exhibiting grossly apparent lung lesions if the pressures rise "slowly" to a maximum and do not have a shock component as a part of the early rising phase of the pulse.

RELATION BETWEEN LUNG INJURY IN DOGS AND AIR-BLAST DOSE



Data from Richmond, DASA Project, Lovelace Foundation,[44] reproduced as Figure 6 by Pratt et al.[45]

Figure 78

TABLE 34

LUNG WEIGHT – OVERPRESSURE RELATIONSHIP IN DOGS EXPOSED INSIDE GROUP SHELTERS 8001 AND 8002 (1957) TO "SLOWLY" RISING OVERPRESSURES OF "LONG" DURATION[5]

Dog No.	Maximum Pressure Nearest Gauge psi	Lung Weight as Per Cent of Body Weight	Gross Lung Pathology Observed – Comments
G-9	4.1	0.92	None
G-10	4.1	1.04	None
K-10	9.0	1.15	None
K-11	9.0	1.04	None
K-12	10.0	1.06	None
K-13	10.0	1.13	None
K-14	10.5	-	None
K-5	23.8	-	None
K-6	23.8	1.11	None
K-7	23.8	0.82	None
K-8	25.6	-	None
K-9	25.6	1.11	None – few petechia microscopically.
K-1	25.7	1.01	Slight lung hemorrhage – back broken by impact. Serious abdominal injuries.
K-2	25.7	-	None – protected by baffle from translation.
K-3	27.0	-	None
K-4	27.0	-	None
G-3	30.2	1.23	None
G-1	30.4	0.91	None
G-2	30.4	1.07	None
G-4	30.5	1.03	None – slight hemorrhage microscopically.
G-5	30.5	0.98	None
G-6	30.5	1.00	None
G-7	30.8	1.02	None
G-8	30.8	1.02	None
Controls		0.98 ±0.2	Total of 14 animals.

Again it is well to point out that the estimates of threshold lung lesions for man are based on animal data obtained at Albuquerque altitude (12 psi) using healthy, young adult dogs. In the future, scaling the data to sea level or other altitudes may very well be justifiable. Also, the incident overpressures that can maximally reflect to the 10 - 12 psi region, as given in Table 28 for Albuquerque altitude, are also scalable to sea-level pressures. And finally, there are no data in either very young or old animals on which to estimate the effect of age, if any, on the pressures associated with minimal blast lesions of the lung.

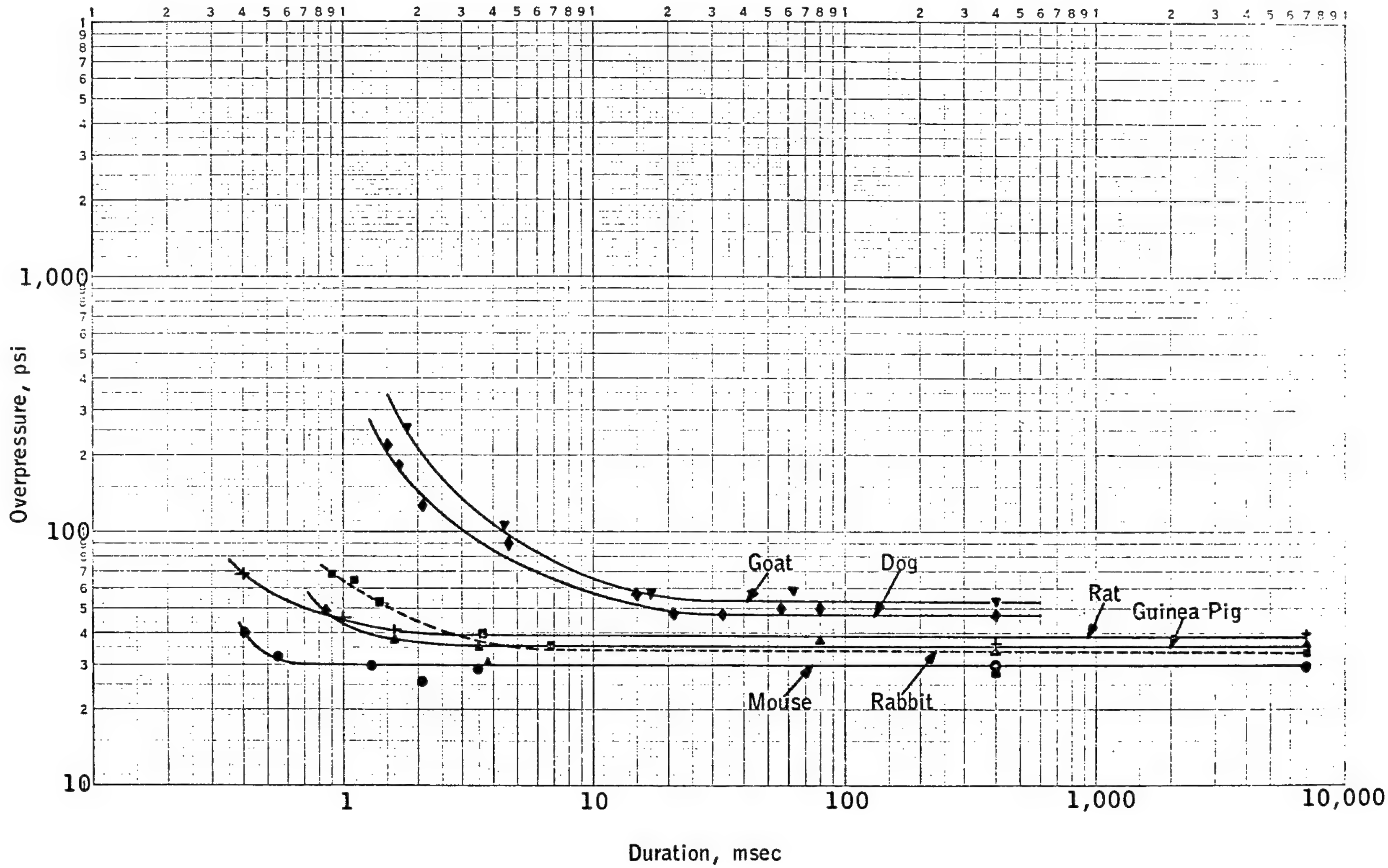
3. Lethality

"Fast"-Rising Overpressures

The data used to estimate the magnitude of "fast"-rising, "long"-duration overpressures likely to be associated with low, intermediate and high levels of human lethality are among those obtained in Albuquerque over the past several years in studies that have defined the pressure-duration relationship for mammals of several species. As recently summarized by Richmond et al.,[13] Figure 79 incorporates results on about 3,000 animals exposed using high explosives detonated above animals lying on an instrumented concrete pad, and a variety of shock tubes with the animals mounted against the plate closing the end of the tube and thus exposed side-on to the pressure pulse.

It is apparent from Figure 79, showing the maximum reflected pressures associated with 50-per cent lethality (P_{50}) as a function of pulse duration for "fast"-rising overpressures, that the pressure required for lethality in all species rises for the shorter-duration waves and that this effect is most apparent for the larger animals. In contrast, the P_{50} is not only fairly constant for the longer-duration pulses, but the differences between "large" and "small" animals becomes much less for durations greater than 50 msec.

This means, of course, that if one were to extrapolate the animal data on the basis of body weight to animals as heavy as man that a spectrum of curves would be obtained with steeper slopes the shorter



Overpressure for 50-per cent lethality as a function of duration for "fast"-rising overpressures[13]

Figure 79

the duration of the pulse wave considered. Such an extrapolation to the 70-kg animal, yielding a P_{50} estimate of 52.3 psi, is shown by the solid line in Figure 80 using the P_{50} points at 400 msec from Figure 79 for mice, rats, guinea pigs, rabbits, dogs and goats.[36] In addition, unpublished P_{50} findings were included for hamsters and cats.[44] All the 727 animals were exposed side-on against the end plate closing a shock tube to reflected pressures enduring for about 400 msec.

Regarding human hazards, the question, of course, is whether man lies substantially above or below the solid curve shown in Figure 80. Because there are no human data applicable to "long"-duration pulses, a range from 42 - 57 psi was arbitrarily taken to be the best estimate of the P_{50} for adult humans as noted in Table 28.

The threshold and near 100 per cent lethality estimates were obtained by using the average slopes of the probit curves obtained for dogs and goats along with the P_{50} figure of 50.5 psi noted above to make estimates for 1 and 99 per cent lethality in terms of overpressure. An arbitrary range was taken on either side of these figures to arrive at the values of 30 - 42 psi and 57 - 80 psi shown in Table 28.

In a recent theoretical study, Bowen et al.[82] used only the dog and goat data of Richmond to estimate the P_{50} for the 70-kg animal by employing a derived relation indicating that for a given overpressure a biologically equivalent pulse duration could be scaled according to the one-third power of the ratio of the masses of the animals. For example, if the duration of the 50 per cent lethal pressure for 16.5-kg dogs was $t_{d_{12}}$ at Albuquerque altitude, then the duration of the wave for a 70-kg mammal would be:

$$t_m = t_{d_{12}} (70/16.5)^{1/3}. \quad (1)$$

To scale this duration to sea level, Bowen's theory requires that the right side of the equation be multiplied by the square root of the ratio of the ambient pressures. Thus, the equation applicable to sea-level conditions for 16.5-kg dogs becomes:

$$t_{m-sl} = t_{d_{12}} (70/16.5)^{1/3} (12.0/14.7)^{1/2} \quad (2)$$

RELATION BETWEEN BODY WEIGHT AND "FAST"-RISING OVERPRESSURES OF 400 MILLISECONDS DURATION NEEDED TO PRODUCE 50 PER CENT MORTALITY

Animals exposed side-on against the plate closing the end of a shock tube

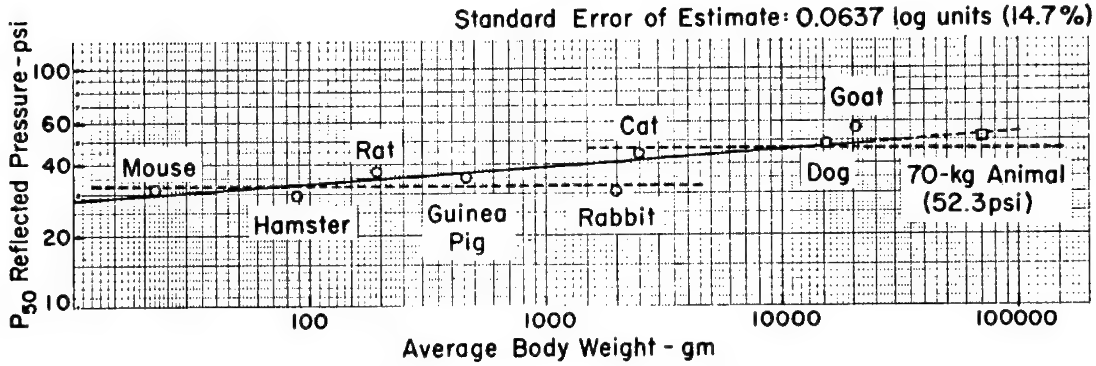
REGRESSION EQUATION

$\text{Log}\ (LD_{50}) = 1.5753 + 0.07755\ \log\ (BW)$

Where LD_{50} = Pressure required for 50% mortality, psi

BW = Average body weight of the group, grams

Standard Error of Estimate: 0.0637 log units (14.7%)



	MOUSE	HAMSTER	RAT	GUINEA PIG	RABBIT	CAT	DOG	GOAT
NO. ANIMALS	140	110	164	96	104	48	35	30
MEAN WEIGHT*	22g±1.9	89g	192g±25	455g±37	1.97kg±0.26	2.48kg	15.1kg±3.1	20.5kg±3.6
P_{50} (PSI) +	30.7±0.56	28.6	36.6±0.61	34.5±0.64	29.6±0.90	43.6	47.8±1.06	53.0±2.79

* Figures represent mean and standard deviation.

\+ The ± figures represent the standard error of the mean.

Figure 80

The t_{m-sl} scaled for 22.2-kg goats would be:

$$t_{m-sl} = t_{g_{12}}(70/22.2)^{1/3}(12.0/14.7)^{1/2}. \qquad (3)$$

Also, the study of Bowen et al.,[82] guided by the empirical work of Damon et al.[46,47] on the effects of ambient pressure on blast tolerance, employed "biological" blast scaling to compute the sea-level equivalent P_{50} figures, P_{50-sl}, from the $P_{50_{12}}$ values obtained by Richmond at Albuquerque altitude using the relationship:

$$P_{50-sl} = P_{50_{12}}(14.7/12.0) \qquad (4)$$

Such a procedure yields an estimated P_{50} figure for the 70-kg animal of 51 psi at 12 psi ambient and 62 psi at sea level (14.7 psi) compared with the extrapolation given in Figure 80 of about 52 psi at 12 psi ambient which scales to near 64 psi at sea level. Thus, both methods of estimating the P_{50} figures for the 70-kg animal agree well for "long"-duration overpressures. But this fact does not answer the question raised by the dotted, horizontal lines arbitrarily drawn in Figure 80; namely, do "larger" and "smaller" animals respond at different quantitative levels to blast overpressures? The theoretical study of Bowen et al.[82] and a variety of data quoted therein strongly suggest that this is a distinct possibility. Thus, one important matter for the future is to decide whether or not "small" animal data should be employed at all in estimating the response of animals as large as man.

Regarding the shorter-duration overpressures — though this matter is not strictly the concern of this paper — it is interesting to call attention to Table 35 giving the P_{50} estimates at ambient pressures of 12 and 14.7 psi using data from all the species as worked out by Richmond et al.[13] on the one hand, and the theoretical approach followed by Bowen et al.[82] employing as input only Richmond's emperical figures applicable to dogs and goats on the other. Figure 81 depicts the uncertainities graphically, and it is clear that many more data are needed to establish the most satisfactory way to estimate blast tolerance for the 70-kg mammal when pulse durations are "short."

Fortunately a few estimated overpressures associated with

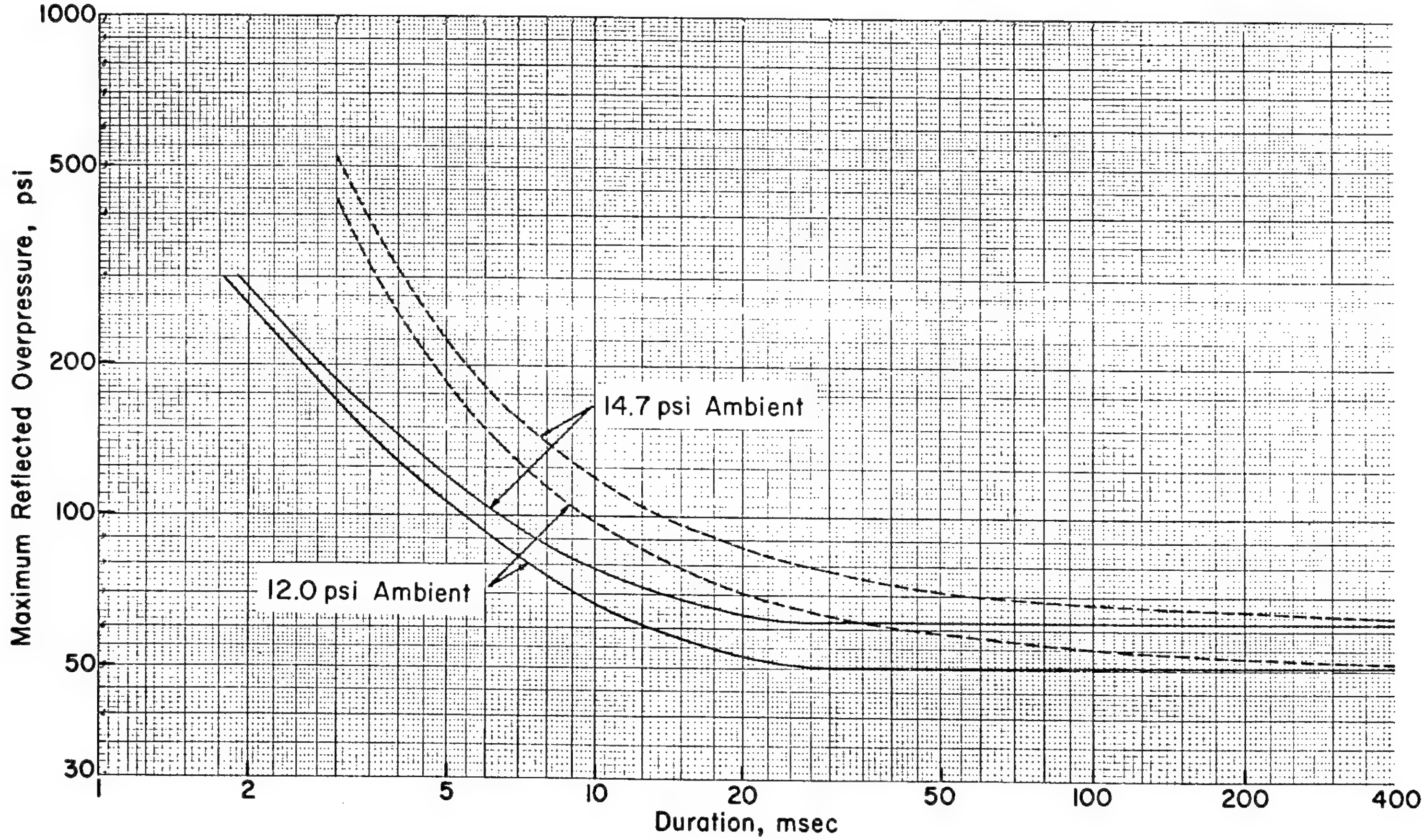
TABLE 35

ESTIMATED P_{50} VALUES FOR "FAST"-RISING OVERPRESSURES OF INDICATED DURATIONS COMPUTED AT AMBIENT PRESSURES OF 12 AND 14.7 PSI BY USING DATA FROM ALL SPECIES AND ONLY THOSE FOR DOGS AND GOATS[82]

Pulse Duration in msec	Estimated P50 Figures for 70-kg Animals in psi at Indicated Ambient Pressures and Approaches: 12 psi*		14.7 psi+	
	From all Species†	From Dogs and Goats**	From all Species†	From Dogs and Goats**
400	52	51	64	62
30	64	51	78	62
20	71	53	87	64
10	98	67	120	79
5	185	106	227	120
3	431	171	528	188

*Albuquerque altitude — 12 psi
+Sea-level ambient — 14.7 psi
†Computed from all species, Richmond et al.[13]
**Computed from dogs and goats, Bowen et al.[82]

ESTIMATES OF THE PARAMETERS OF REFLECTED, "FAST"-RISING BLAST WAVES RESULTING IN 50% MORTALITY OF 70-kg MAMMALS AT 12.0 AND 14.7 psi AMBIENT PRESSURES



------- Extrapolated from all species, Richmond et al.[13]
——— Scaled from dog and goat data, Bowen et al.[79]

Figure 81

human exposures are available from the World War II literature, but the durations of the pulse and leading edge of the pressure rise remain unknown and subtract from the validity of the figures, some of which are set forth below.

Fisher, Krohn and Zuckerman[33,83] from field studies noted 12 human exposures to bombs dropped on British cities and estimated the maximum pressures for each. These ranged from 170 to 500 - 600 psi. There was one fatality at 450 psi, 10 survivors between 150 and 450 and one between 500 - 600 psi.

By extrapolating animal data obtained with small charges (1 to 3 msec pulse durations), the same authors estimated tolerance to be 390 psi for the 60- and 470 psi for the 80-kg animal.[33,83]

Desaga[17] described the exposure of a gun crew of 13 men in an open-topped, antiaircraft gun revetment to two bomb detonations, only one of which was regarded as significant. The positions of 8 of the individuals were known. Two were lethally injured while the other 6 survived. From an estimation of the pressure-time conditions involved, Desaga[17] placed the "lethal limit" for man at 100 psi when the pulse duration was between 6 - 7 msec.

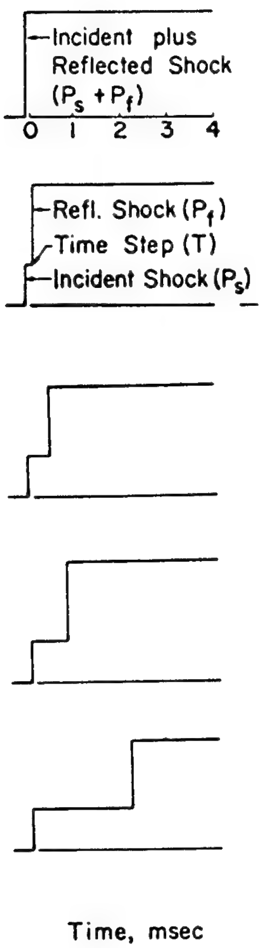
Though the data of Desaga[17] and Fisher et al.[33,83] are not inconsistent with the estimates of Richmond[13] and Bowen[82] as can be seen from Figure 81, there is little point in belaboring the argument further. Not only are additional biological data needed — particularly for "short"- duration overpressures — to learn more about man's tolerance including which mammal or mammals respond most like the human case, but more biophysical information must be sought to spell out, among other things, how much of the falling phase of a "fast"-rising pulse is significant to the biological target. For example, it is doubtful that the last 25 msec of a 100-msec pulse of classical shape "means" much to an animal. To the contrary, there can be little doubt that the first 25 msec, maybe less, of the pulse is very important indeed. It is difficult, from present knowledge, to say anything definitive about the middle 50 msec of the wave, but it is mandatory that the search continue for answers to questions of this kind.

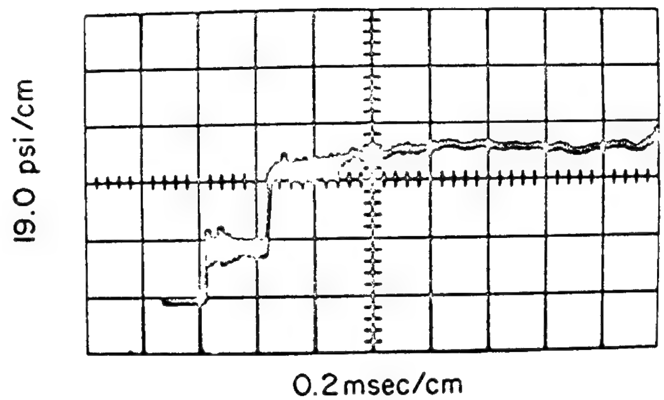
Stepwise Increases in Overpressures

The statement that stepwise increases in "long"-duration overpressures, such as occur when an animal is exposed at increasing distances away from an end plate of a shock tube, can be associated with an increase of 60 - 65 per cent in blast tolerance, is based on the work of Richmond and associates[32,39] with rodents. For example, Figure 82 illustrates the leading edges of the "long"-duration wave forms involved. Table 36, giving the incident and maximum reflected overpressures found to be associated with 50-per cent lethality for guinea pigs exposed side-on against — and 1, 2, 3, 6 and 12 inches from — the end plate of a shock tube, shows that tolerance increased from about 37 to 57 - 59 psi or 60 - 65 per cent.

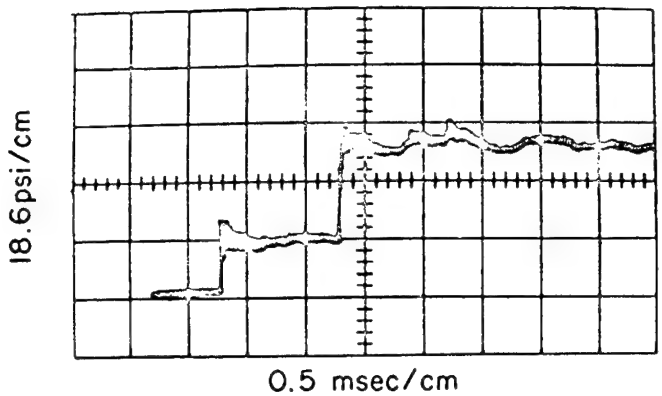
To date, there has not been any exposure of significant numbers of larger animals to "stepwise" pressure pulses, but experience with a few dogs subjected to somewhat similar pulses also indicated a noteworthy increase in tolerance.[44] Figure 83, giving the P_{50} reflected overpressure for guinea pigs as a function of the time between the first (incident) and second (reflected) pulse, implies that if the two steps are closer together than 0.2 msec, the animal "appreciates" them as one.[13] To the contrary, if the time interval is longer than 0.2 msec and up to 0.5 msec, the two pulses are "considered" separately in that the presence of the first increases tolerance to the second by a significant amount. Such data for the dog are too few to be meaningful, but a suggestion as to what might be expected is also shown in Figure 83.

A quite significant series of experiments with 4 species of rodents were performed by Richmond et al.[32] in which all the animals were exposed, within a few psi, to the same incident pressure of about 18 psi and the associated reflected pulse of 52 psi, adding near 34 psi as a second step to the pressure load. Animals were either exposed side-on against the plate closing the shock tube or at various distances in front of the reflecting surface. Thus, only the time between the first and second pulse was the experimental variable. As shown in Figure 84, all species suffered 100-per cent lethality when exposed against the end plate. For each, there was a distance from the end plate beyond which lethality dropped sharply. For example, in the case of the mouse at 1/2 in., lethality was about 62 per cent; at 1 in., near 30 per cent; at 2 in.,





(a) Gauge located 1.5 inches from the Reflecting Plate[39]



(b) Gauge located 7.5 inches from the Reflecting Plate[39]

Wave forms illustrating almost instantaneous and stepwise increases in overpressure.[2]

Figure 82

Table 36

MORTALITY DATA FOR GUINEA PIGS FOR "FAST"-RISING, "LONG"-DURATION SHOCK TUBE-PRODUCED OVERPRESSURES WHEN THE INCIDENT AND REFLECTED OVERPRESSURES ARE APPLIED IN TWO STEPS[2,32]

DISTANCE FROM END PLATE, IN.	NO. OF ANIMALS	OVERPRESSURES ASSOCIATED WITH 50% MORTALITY IN psi			TIME BETWEEN APPLICATION OF INCIDENT AND REFLECTED PRESSURES, msec
		P_i	P_r	$P_r - P_i$	
0	140	12.1	36.7 ± 0.7*		0
1	75	13.4	40.8 ± 2.1	27.4	0.10**
2	78	15.6	48.3 ± 1.3	32.7	0.20
3	87	16.9	52.8 ± 1.9	35.9	0.30
6	99	18.7	58.6 ± 1.6	39.9	0.63
12	109	18.2	57.1 ± 1.1	38.9	1.36

* All plus or minus figures refer to the standard error of the mean.
** Estimated.
P_i = incident pressure; P_r = reflected pressure; $P_r - P_i$ = magnitude of the second stepwise increase in pressure.

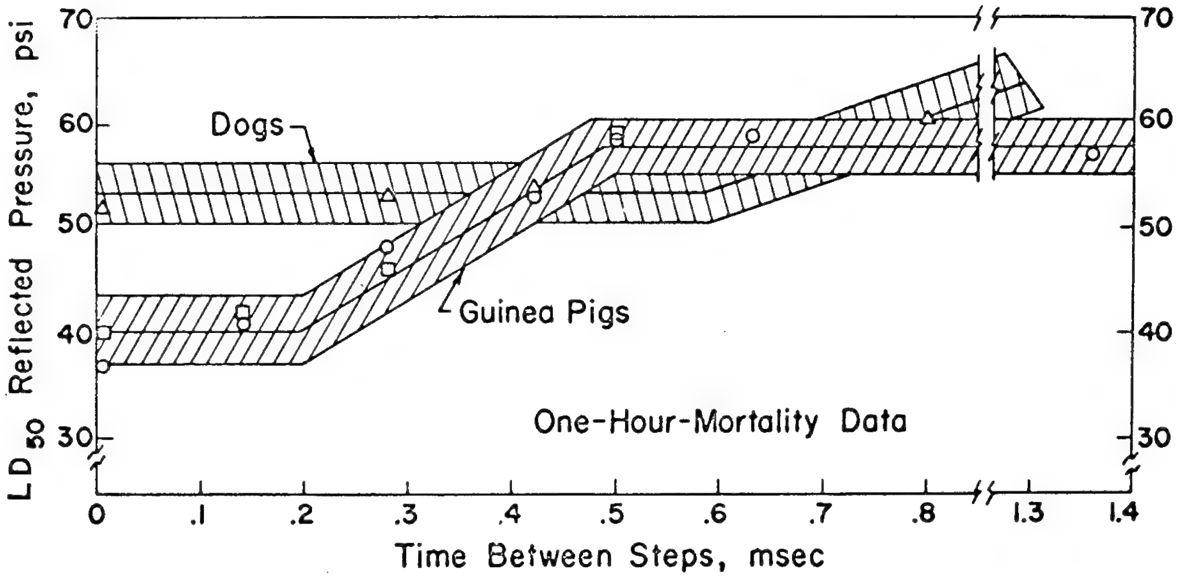
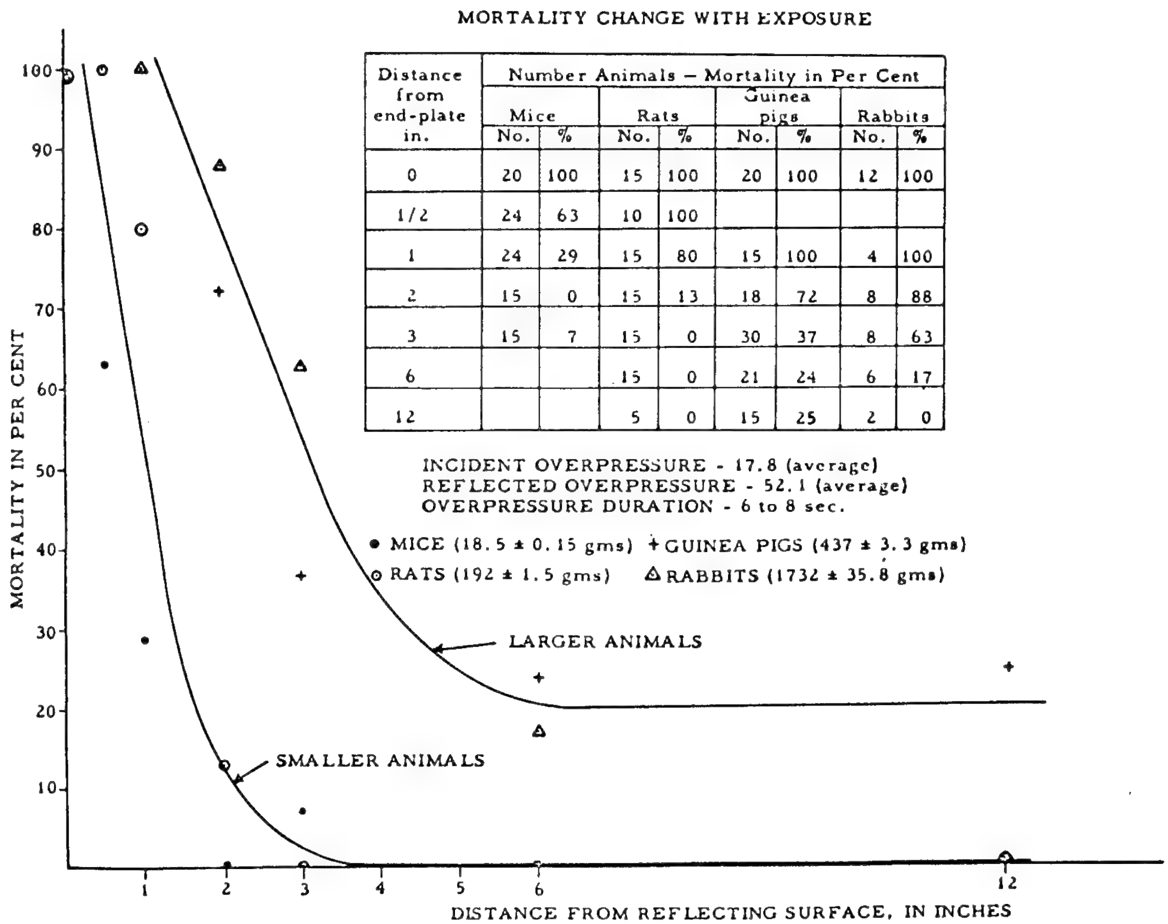


Figure 83 — *Tolerance of animals to overpressures applied in two steps.* (Ref. 13)



Distance from end-plate in.	Number Animals – Mortality in Per Cent							
	Mice		Rats		Guinea pigs		Rabbits	
	No.	%	No.	%	No.	%	No.	%
0	20	100	15	100	20	100	12	100
1/2	24	63	10	100				
1	24	29	15	80	15	100	4	100
2	15	0	15	13	18	72	8	88
3	15	7	15	0	30	37	8	63
6			15	0	21	24	6	17
12			5	0	15	25	2	0

Figure 84 — *Mortality variations for animals exposed against and at indicated distances from the end plate closing the end of a shock tube. Incident and reflected overpressures varied from 16.6 to 18.7 and 48 to 55 psi, respectively, and endured for 6 to 8 sec.* (Ref. 2, 32)

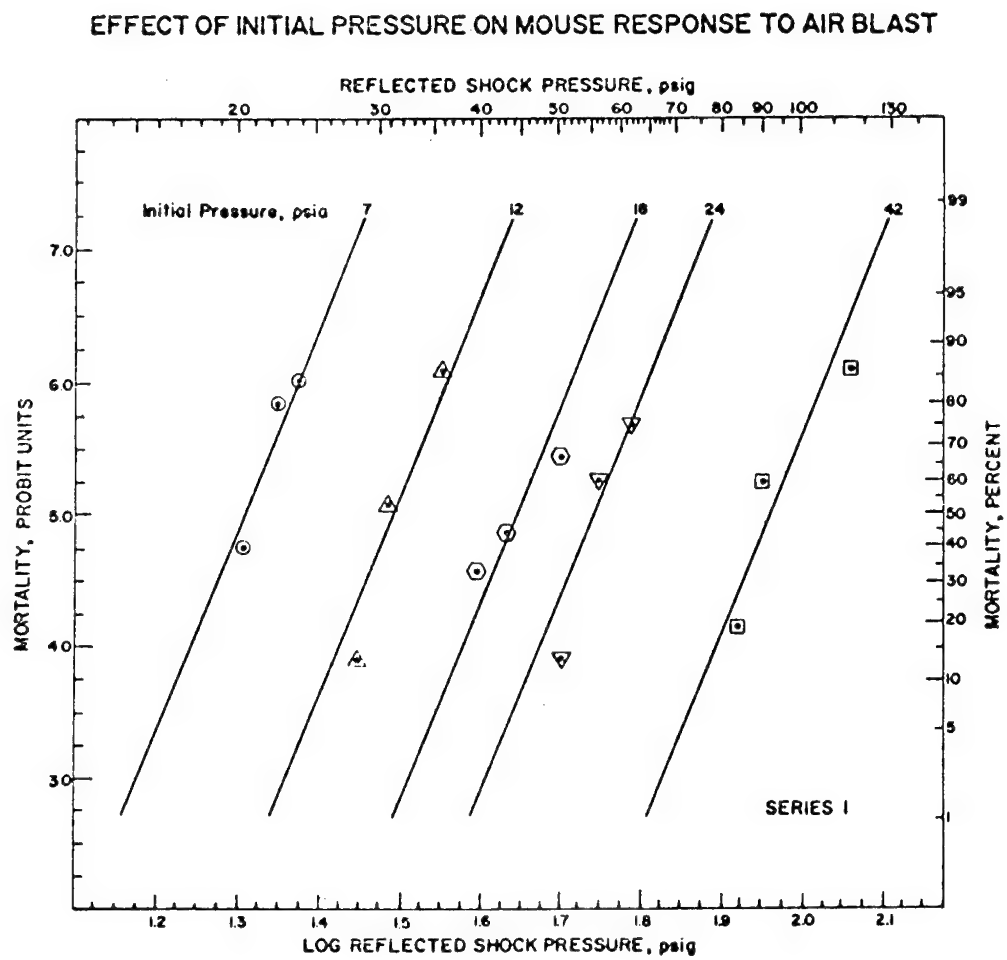
zero; and at 3 in., about 8-per cent mortality was recorded. It is a remarkable fact that in 50 microsec (at 0.5 in.) and 100 and 200 microsec (at 1 and 2 in., respectively), an adaptation occurs in the mouse in response to the incident pressure which protects him either partly or completely from the reflected pulse, which if given alone would be almost invariably fatal. Since the other species exhibited similar behavior and because the finding has practical significance — i.e., avoid exposure to overpressures close to or against a reflecting surface — it is important to learn more about the phenomena of step loading in larger animals.

The Ambient Pressure Experiments

One might assume that the body walls of the rodents studied were driven inward and the diaphragms upward by the incident pulse in the experiments noted above, and that as a consequence the internal air pressure in the lung increased significantly before the second pulse arrived. If this were so and the animal were thus making an adaptation by "creating," so to speak, a higher, internal, ambient pressure, then one might reason, first, that tolerance increased because the ratio of the external to the internal pressure was changed and, second, that experiments done at ambient pressures lower and higher than the ambient of 12 psi at Albuquerque should show lower and higher P_{50} figures, respectively.

Damon et al.[47] have performed and published such experiments with mice. The results, as a series of probit curves, are shown in Figure 85 for ambient exposure pressures of 7, 12, 18, 24 and 42 psi. As noted in Table 37, summarizing the P_{50} figures, tolerance of about 20 psi for an ambient pressure of 7 psi progressively rose, as the ambient pressure was increased, to reach near 92 psi when the exposure ambient was 42 psi. Thus with a sixfold increase in the pressure at which exposure occurred, there was between a four- and fivefold increase in the overpressure required for 50-per cent lethality.

If the results are normalized to show the ratio of the external P_{50} pressure to the internal pressure existing at the time of exposure — which was very close to the ambient — then the $\Delta P/P_i$ values range from 2.9 down to about 2.2 as noted in the last column of Table 38.



Probit regression lines relating mortality in percent and in probit units to the log of the reflected shock pressures for mice subjected to air blast at different initial air pressures.[47]

Figure 85

TABLE 37

RESULTS OF PROBIT ANALYSIS OF THE SERIES I DATA SHOWING EFFECTS OF AMBIENT PRESSURE ON BLAST TOLERANCE OF MICE[47]

Initial Pressure, psia	Number of Animals	LD_{50}-1-hour Reflected Pressure (ΔP), psig	Probit Equation Constants	
			intercept, a	slope, b
7	60	20.3 (19.0-21.5)*	-14.481	14.889**
12	45	31.0 (29.3-33.3)	-17.254	14.889
18	48	44.5 (41.9-47.4)	-19.543	14.889
24	60	55.3 (52.4-58.3)	-20.948	14.889
42	57	91.8 (86.1-98.3)	-24.225	14.889
Total	270			

*Numbers in parentheses are the 95-per cent confidence limits.
**Standard deviation of the slope constant, b = ±2.154.

TABLE 38

NORMALIZED LD_{50} VALUES FOR MICE AT VARIOUS AMBIENT PRESSURES[47]

Initial Pressure, P_i, psia	LD_{50}-1-Hour Overpressure	
	ΔP, psig	atm*($\Delta P/P_i$)
7	20.3	2.90
12	31.0	2.60
18	44.5	2.47
24	55.3	2.30
42	91.8	2.19
	Average	2.49

*Atmospheres of the initial pressure.

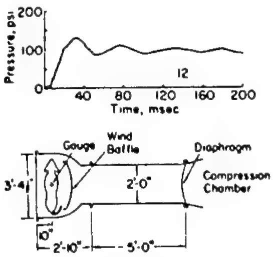
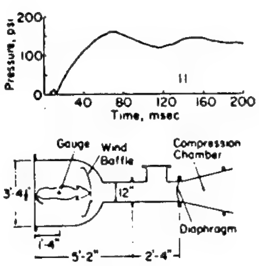
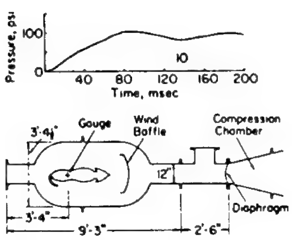
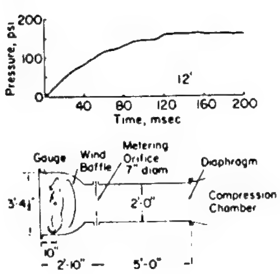
"Slowly" Rising Overpressures of "Long"-Duration

Though eardrum rupture, sinus hemorrhage and some hemorrhage in the lower margins of the lungs may occur, "long"-duration overpressures rising smoothly, or as a series of small steps, are tolerated reasonably well by dogs. For example, the left-hand side of Figure 86 shows 4 wave forms to which dogs were exposed by Richmond et al.[48] in exploratory experiments several years ago. As can be seen from the last column of Figure 86 and Table 39, no lethality occurred, but other events including minor pulmonary hemorrhage were recorded. Pressures as high as 170 psi were tolerated which is between three- and fourfold greater than the P_{50} value of 47.8 given in Figure 80 for "fast"-rising, "long"-duration pulses.

In fact, as noted in the series of diagrams and tabular material in Figure 87, the dog has survived pressures as high as 230 psi, but only <u>if</u> the time to maximal pressure is sufficiently delayed and <u>if</u> the incident and reflected shock pressures as defined in the idealized pressure-time curve reproduced in Figure 88 are below the lethal range. Thus, the data in Figure 87 show clearly that either survival <u>or</u> death may be associated with overpressures between four- and fivefold the minimal shock pressure for 50 per cent lethality (47.8 psi) depending mostly upon the character of the early portions of the pressure rise. In this regard, a study of the tabular data in Figure 87 shows that if the time to maximal pressure is less than 20 or 30 msec, or if the initial reflected shock pressure ranges up to or above 30 - 50 psi, lethality is quite likely to occur.

Orbital Fractures

In the body of Figure 87 and summarized in Table 40, are data associated with the discovery of orbital fractures in dogs by Richmond.[49] The lesions, shown in the fresh state in Figure 89 and in the orbital bones alone in Figure 90, were only noted at maximum pressures above 140 psi providing the time to maximal pressure was 30 msec or less. Also the fractures were recorded both in living animals post-shot and in those lethally injured by the blast depending, as has been pointed out previously, upon the character of the early rising phase of

Exposure geometry, and pressure-time profiles	Overpressure, psi Incident shock (P_s)	Reflected shock (P_r)	Maximum (P_m)	Time to maximum pressure msec (T_{Pm})	Duration of over-pressure sec (T_d)	Blow-out fracture R	L	Subcon-junctival hemor-rhage R	L	Remarks and total number animals in each group
	-	-	74	29	10					All four animals survived
	-	-	86		(approx.)					4 animals total
	-	-	112							
	-	-	130							
	-	-	130	62	10					All four animals survived
	-	-	170		(approx.)					4 animals total
	-	-	160							
	-	-	163							
	-	-	110	86	20					All four animals survived
	-	-	118		(approx.)					4 animals total
	-	-	151							
	-	-	156							
	-	-	116	155	5					All four animals survived
	-	-	147		(approx.)					4 animals total
	-	-	155							
	-	-	167							

•Denotes the absence of "clean" incident or reflected shocks in the pressure pulse.

Gross biological response following exposure of dogs to "slowly" rising overpressures of "long" duration. [48, 49]

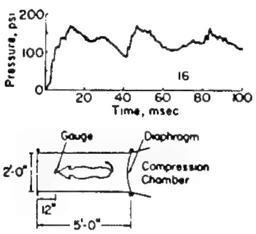
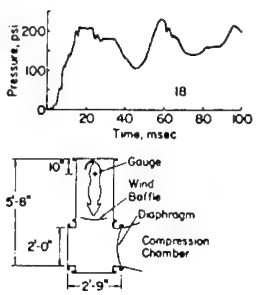
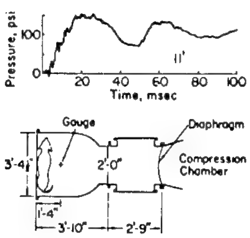
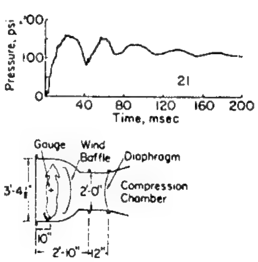
Figure 86

TABLE 39

EFFECTS ON DOGS OF LONG DURATION OVERPRESSURE APPLIED AT DIFFERENT RATES[48]

DOG NO.	BODY WEIGHT (kg)	MAXIMUM OVER-PRESSURE, (psi)	TIME TO MAXIMUM PRESSURE, (msec)	AVERAGE RATE OF PRESSURE RISE (psi / sec)	DURATION OF OVER-PRESSURE, (sec)*	PATHOLOGY				
						Ruptured Ear Drums Right	Ruptured Ear Drums Left	Hemorrhagic Sinus	Petechia Lining Larynx	Pulmonary Hemorrhage
T–24	16.5	116	154	753	5	+	+	+	+	–
T–25	17.9	147	158	930	5	+	+	+	+	–
T–26	16.5	155	152	1020	5	+	+	++	+	–
T–27	16.7	167	155	1077	5	+	+	++	–	–
T–1	20.4	110	84	1310	20	+	+	+	+	–
T–2	19.3	118	85	1388	20	+	+	+	+	–
T–4	19.3	151	90	1678	20	+	+	++	–	+
T–5	15.6	156	86	1814	20	+	+	++	–	+
T–6	16.5	130	64	2031	10	+	+	+	–	+
T–7	19.5	170	60	2833	10	+	+	++	+	+
T–8	20.8	160	60	2667	10	+	+	++	+	+
T–9	16.1	163	63	2587	10	+	+	++	+	+
T–13	22.5	74	27	2741	10	+	+	+	–	–
T–15	20.2	86	28	3071	10	+	+	+	+	–
T–19	18.1	112	30	3733	10	+	+	+	+	+
T–20	20.2	130	30	4333	10	+	+	+	+	+

* Approximate–measured with a stop watch
– Lesion not present
\+ Lesion slight. Also indicates rupture of the tympanic membrane
++ Lesion marked

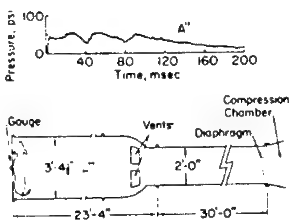
Exposure geometry, and pressure-time profiles	Overpressure, psi: Incident shock (P_s)	Overpressure, psi: Reflected shock (P_r)	Overpressure, psi: Maximum (P_m)	Time to maximum pressure msec (T_{Pm})	Duration of over-pressure sec (T_d)	Blow-out fracture R	Blow-out fracture L	Subcon-junctival hemor-rhage R	Subcon-junctival hemor-rhage L	Remarks and total number animals in each group
	-	-	168	12	120	+		+		Survived
	-	-	230		(approx.)	+	+	+	+	Survived
										2 animals total
	-	-	130* (90-150)	17	30 (approx.)					All four animals survived
	-	-	204							Survived
	-	-	204			+		+	+	Survived
										6 animals total
	-	-	143	19	10	+		+		A blast death
	-	-	147		(approx.)					Survived
										2 animals total
	-	-	91	19	8					All 5 animals survived. Sustained internal injuries from impact following translation
	-	-	92		(approx.)					
	-	-	142							
	-	-	148							
	-	-	161							5 animals total

*Mean with the range below in parentheses
-Denotes the absence of "clean" incident or reflected shocks in the pressure pulse
+Represents a positive finding, whereas a blank space denotes a negative finding

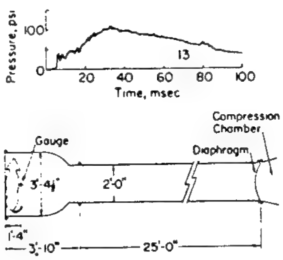
(continued on next page)

The relation between orbital fractures, exposure geometry and pressure-time parameters[49]

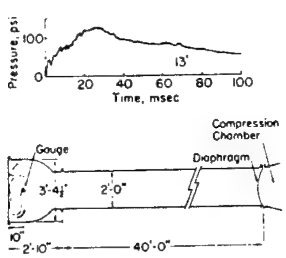
Figure 87



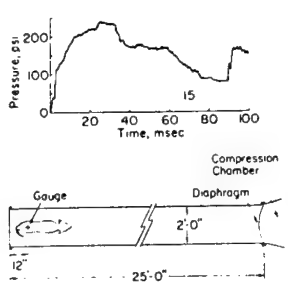
Exposure geometry, and pressure-time profiles	Overpressure, psi: Incident shock (P_s)	Overpressure, psi: Reflected shock (P_r)	Overpressure, psi: Maximum (P_m)	Time to maximum pressure msec (T_{Pm})	Duration of over-pressure sec (T_d)	Blow-out fracture R	Blow-out fracture L	Subcon-junctival hemor-rhage R	Subcon-junctival hemor-rhage L	Remarks and total number animals in each group
	16* (14-17)	42 (39-45)	52 (45-58)	22	.382					One blast death among 15 animals
	18 (17-20)	50 (47-55)	72 (66-77)		.419					15 blast deaths among 20 animals
										35 animals total



Exposure geometry, and pressure-time profiles	Overpressure, psi: Incident shock (P_s)	Overpressure, psi: Reflected shock (P_r)	Overpressure, psi: Maximum (P_m)	Time to maximum pressure msec (T_{Pm})	Duration of over-pressure sec (T_d)	Blow-out fracture R	Blow-out fracture L	Subcon-junctival hemor-rhage R	Subcon-junctival hemor-rhage L	Remarks and total number animals in each group
	21* (15-28)	46 (31-63)	120 (74-157)	26	5 (approx.)					Two blast deaths among 10 animals
	23	56	163						+	Survived
	32	74	165							A blast death
	22	56	166							Survived
	32	62	170					+		A blast death
	24	62	171							Survived
	29	63	171			+	+	+	+	A blast death
	28	68	195				+		+	A blast death
										17 animals total



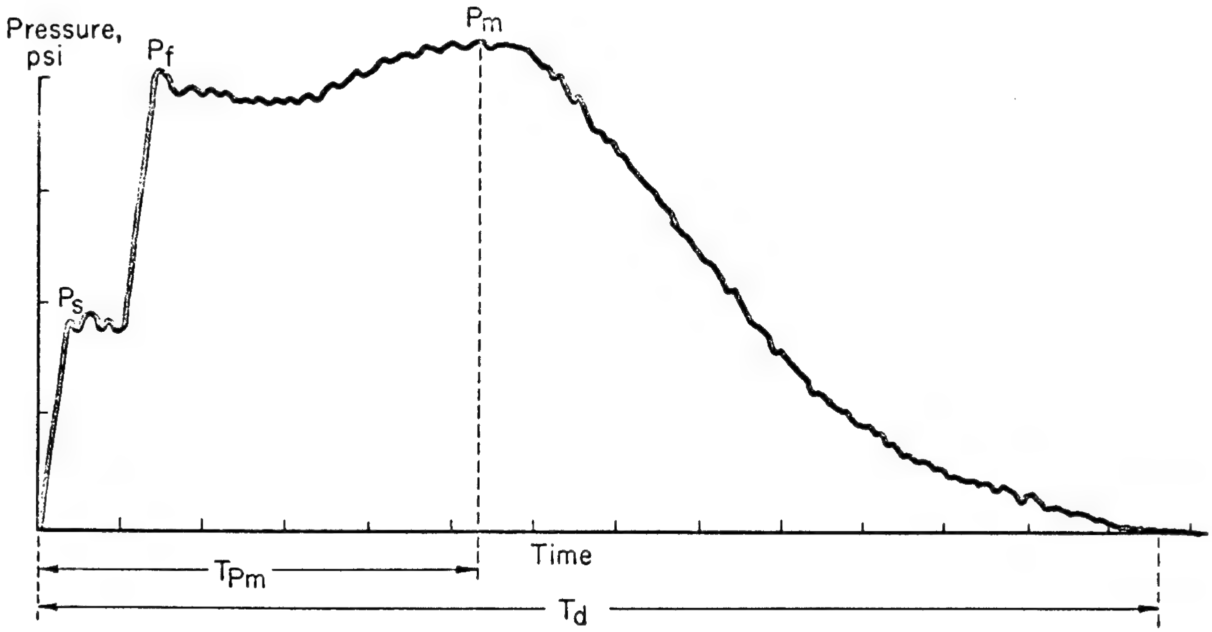
Exposure geometry, and pressure-time profiles	Overpressure, psi: Incident shock (P_s)	Overpressure, psi: Reflected shock (P_r)	Overpressure, psi: Maximum (P_m)	Time to maximum pressure msec (T_{Pm})	Duration of over-pressure sec (T_d)	Blow-out fracture R	Blow-out fracture L	Subcon-junctival hemor-rhage R	Subcon-junctival hemor-rhage L	Remarks and total number animals in each group
	16* (12-20)	34 (27-45)	96 (74-120)	26	24 (approx.)					One blast death among 9 animals
	21* (14-29)	43 (31-56)	138 (124-157)		27 (24-30)					Five blast deaths among 8 animals
	27	56	165		27					A blast death
	20	43	166		(approx.)		+		+	A blast death
	28	40	166							A blast death
	28	54	167							A blast death
	22	43	171							A blast death
	NR	43	177							A blast death
										23 animals total



Exposure geometry, and pressure-time profiles	Overpressure, psi: Incident shock (P_s)	Overpressure, psi: Reflected shock (P_r)	Overpressure, psi: Maximum (P_m)	Time to maximum pressure msec (T_{Pm})	Duration of over-pressure sec (T_d)	Blow-out fracture R	Blow-out fracture L	Subcon-junctival hemor-rhage R	Subcon-junctival hemor-rhage L	Remarks and total number animals in each group
	18.2* (17-20)	62.0 (58-74)	106 (82-140)	26	30 (approx.)					All five animals survived
	28	110	197					+	+	Survived
	30	102	198			+		+		Survived
	26	114	200							A blast death
	30	114	231			+		+		A blast death
										9 animals total

*Mean with the range below in parentheses
NR Indicates there was no record taken of the incident shock
+Represents a positive finding, whereas a blank space denotes a negative finding

Figure 87 (continued)[49]



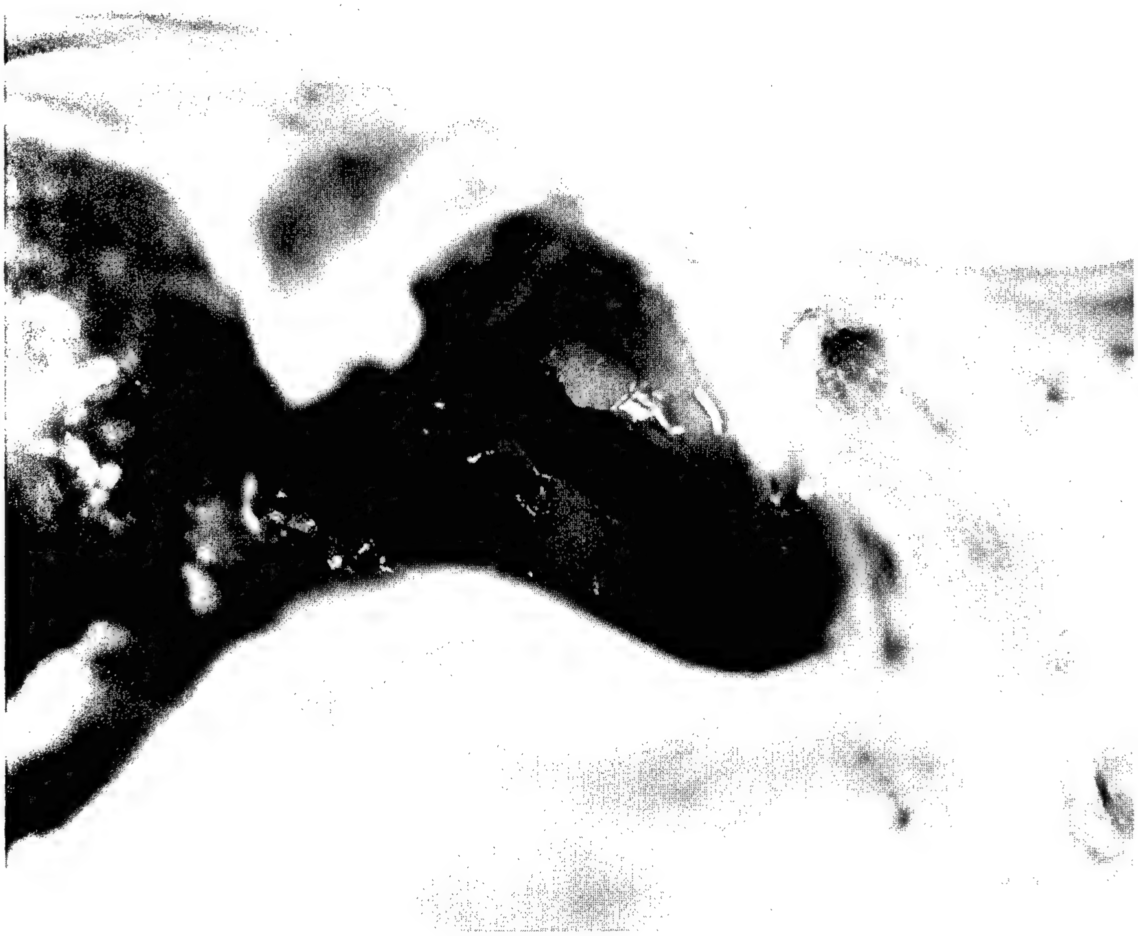
P_s = Incident shock pressure, psi
P_f = Reflected shock pressure, psi
P_m = Maximum pressure, psi
T_{Pm} = Time to maximum pressure, milliseconds
T_d = Duration of pressure, milliseconds or seconds

Figure 88 – *Idealized atypical pressure-time curve* [2,49]

Table 40 – THE OCCURRENCE OF ORBITAL FRACTURES IN DOGS AS RELATED TO THE PEAK PRESSURE AND THE TIME TO PEAK PRESSURE [2,49]

OVER-PRESSURE, psi	NUMBER OF FRACTURES AT THE INDICATED TIMES TO PEAK PRESSURE					
	10 to 20 msec		21 to 30 msec		31 to 160 msec	
	No. of animals	No. with orbital fractures	No. of animals	No. with orbital fractures	No. of animals	No. with orbital fractures
41 to 60	0	0	15	0	0	0
61 to 80	0	0	25	0	0	0
81 to 100	3	0	8	0	0	0
101 to 120	0	0	9	0	3	0
121 to 140	1	0	6	0	1	0
141 to 160	6	1	8	0	5	0
161 to 180	2	1	12	2*	3	0
181 to 200	1	0	3	2	0	0
201 to 220	2	1	0	0	0	0
221 to 240	1	1*	1	1	0	0
TOTALS	16	4	87	5	12	0
Percent (animals)		25		5.7		0
Percent (orbits)		15.6		3.4		

*Denotes one case in which there were orbital fractures bilaterally.



Orbital fracture into the dog's nasal cavity seen after enucleation of the eye[49]

Figure 89

Blast-induced orbital fracture in dogs[49]

Figure 90

the pulse.

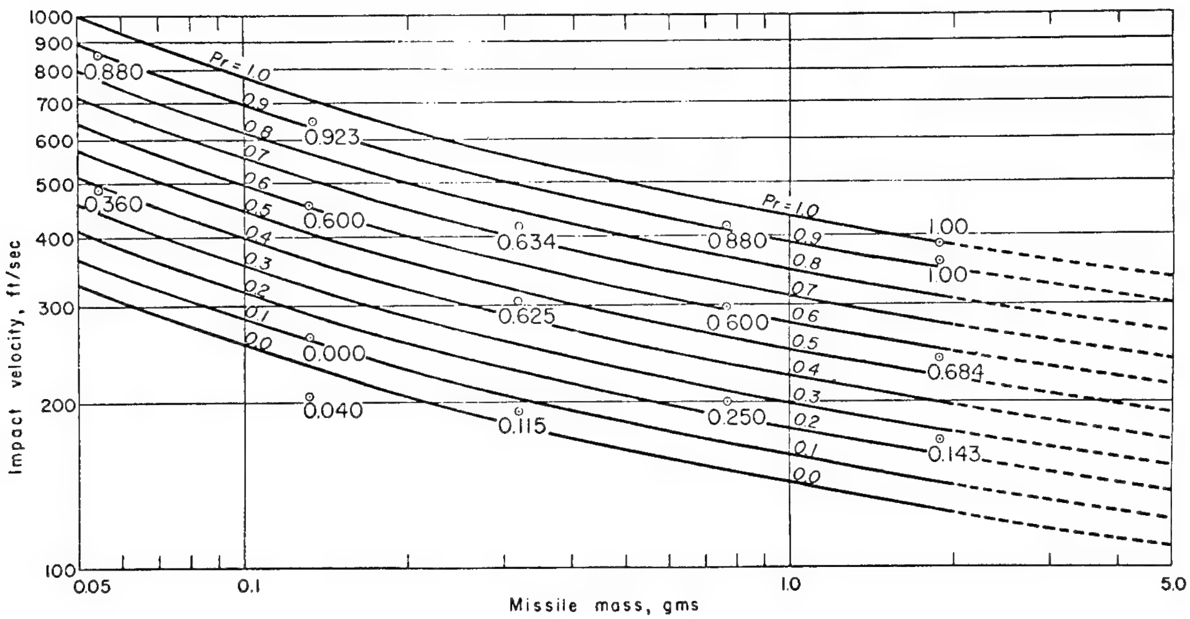
Though Campbell[84] according to Osborn[85] has reported fracture of the orbital plate of the frontal bone in man exposed to blast, there are no relevant quantitative data. Those interested in more information are referred to the paper of Richmond et al.[49] in which literature concerning the tolerance of the eye and orbit to blast and trauma is reviewed in some detail.

B. Secondary Blast Effects

1. Penetrating Missiles

Since entry of one of the serous cavities of the body or penetration of the eye can be regarded as a serious wound at least because infections almost always occur, the criteria for penetrating missiles noted in Table 29 were formulated in terms of frangible materials of which window glass is an example.[2, 11, 12, 14, 31] To arrive at the figures used, advantage was taken of a study by Bowen et al.[51] in which the probability of penetration into the abdominal cavity of dogs was determined for small, glass fragments. The impact-velocity-mass relationships established are shown in Figure 91 and summarized in Table 41. Those interested in wounds produced by high- and intermediate-velocity projectiles are referred to a recent text, Wound Ballistics,[86] wherein appears an excellent summary of the many data now available.

Journée[87] reported effects of bullets noted in human cadavers when the mass and impact velocity were as shown in Table 42. Stewart[88] determined the mass-velocity relationships for metal spheres and cubes required to puncture the eyeball of rabbits (see Table 43). The cadaver and eye data, being reasonably consistent with those for glass noted above, along with results of a field experiment with glass missiles at the Nevada Test Site reported by Goldizen et al.,[50] all lend realism to the decision to illustrate the tentative criteria for penetration in terms of a 10-gm (150-grain) glass fragment moving at velocities high enough to lacerate the skin and to penetrate up to at least 1 cm of soft tissue. This distance is near the average thickness of the abdominal wall of dogs and



Probability of penetration of glass fragments into the abdomen of a dog as a function of missile mass and impact velocity. 51

Equation $\log v = 2.5172 - \log(\log m + 2.3054) + 0.4842\, P$

Where $v =$ the impact velocity in feet per second,

$m =$ the mass of glass fragments in grams, and

$p =$ the probability of penetration.

Standard Error of Estimate: 0.0745

Figure 91

TABLE 41

VELOCITY-MASS PROBABILITY RELATIONSHIPS REQUIRED FOR SMALL WINDOW-GLASS FRAGMENTS TO TRAVERSE THE ABDOMINAL WALL AND REACH THE PERITONEAL CAVITY OF DOGS*

Mass of glass fragments, g	Impact velocities for indicated probabilities of penetration in per cent, ft/sec		
	1 per cent	50 per cent	99 per cent
0.05	320	570	1000
0.1	235	410	730
0.5	160	275	485
1.0	140	245	430
10.0	115	180	355

*Data from Report AECU-3350.[51]

TABLE 42

EFFECTS OF MISSILES ON HUMAN CADAVERS*

Type missile	Mass, g	Velocity, ft/sec	Effect on man
Spherical bullets	8.7	190	Slight skin laceration
	8.7	230	Penetrating wound
	7.4	360	Abrasion and crack of tibia
	7.4	513	Travels through thigh
Bullets	6–10	420–266	Threshold for bone injury
	6–15	751–476	Fractures large bones

*Data from Journée.[87]

TABLE 43

IMPACT VELOCITY REQUIRED FOR PUNCTURING RABBIT EYEBALL EMBEDDED IN GELATIN*

Shape of steel missile	Mass		V_{50} impact velocity, ft/sec	Effect on rabbit eye
	Grains	Grams		
Sphere	0.85	0.06	350	Fifty per cent chance of puncturing wall of eyeball with loss of aqueous humor (fluid).
Sphere	16.0	1.04	152	
Cube	2.1	0.14	205	
Cube	4.2	0.27	123	
Cube	16.0	1.04	119	
Cube	64.0	4.15	73	
Cube	255.0	16.52	93	

*Data from Stewart, Report CWLR 2332.[88]

a missile moving fast enough to reach the peritoneal cavity of the animal is likely to invade the abdominal and thoracic cavities of thin individuals.

2. Nonpenetrating Missiles

As noted earlier, choice of the head as the critical organ in case of nonpenetrating missile impact may have to be revised when quantitative data for blunt blows over the liver, spleen, and abdomen generally, become available. In the meantime, however, enough data concerning the impact of blunt objects exist to lend some meaning to tentative criteria exemplified using 10-lb objects* striking the head.

For example, Black, Christopherson and Zuckerman,[59] from a review of British mine accidents, stated a skull fracture occurred from a striking mass of about 8 lb when the latter delivered a fore and aft blow traveling about 15 ft per second, a velocity equivalent to a fall of about 3.5 ft. Also, Zuckerman and Black,[53] using monkeys strapped against a metal plate energized by the impact of a heavy pendulum, failed to produce either skull fracture or signs of concussion with "initial" velocities of 10 ft per second.

Draeger et al.[58] subjected two cadavers lying face down and face up on a table to an "initial" average velocity of near 15 ft per second using a very heavy hammer swung as a pendulum to strike the tabletop from below. In the face-up position, no bone damage was reported. To the contrary, a linear fracture of the vault of the occipital region of the skull occurred in the face-down position.

Gurdjian, Webster and Lissner,[89] in a study dealing with the mechanism of linear skull fracture from low-velocity, blunt blows of energy low enough to cause only transient local deformation of the bone, pointed out that as little as 25 inch-pounds of energy had produced fracture in dry skulls, but that close to 400 - 900 inch-pounds of energy were required to fracture cadaver heads. In another study,[54] the same authors noted that if the imput of energy to the human head was kept below 400 inch-pounds, a considerable reduction in fatalities and serious injuries

*Near the average weight of the human head which ranges from 7 - 15 lb.

would result, a statement in agreement with Lissner and Evans[52] who felt that neither severe concussion nor fracture would result if the impact loading of the skull were 400 inch pounds or less. In terms of a 10-lb mass, about the average weight of the human head, this is equivalent to a drop of 40 inches or an impact velocity of 14.7 ft/sec. In interpreting these figures and those used in the criteria noted in Table 29, one should know that there are uncertainties involved — not least of which are the variations in skull strength, being minimal for mid-frontal blows and maximal for the anterior interparietal positions. Even so, it is likely that unless sharp and irregular objects are involved,[90] the 10- and 15-ft per second figures represent quite-tolerable and threshold-for-injury conditions, respectively. One also draws confidence from the fact that helmeted subjects have voluntarily tolerated blows to the helmet involving velocities of 11 to 14 ft per second. Such findings, attributed by Roth[91] to Lombard, involved an acceleration distance of near 0.1 ft, force application time close to 17 msec, and a maximum load ranging from 15 to 35 G.

Finally, regarding nonpenetrating missiles, it is instructive to note Table 44 summarizing a few data obtained with 0.8- to 0.4-lb croquet ball-like and similar missiles impacted against the lateral thoracic wall of dogs. Velocities to produce local contusion of the lung — 45 ft per second for the heavier and 80 ft per second for the lighter missile — along with the impact velocities for more severe effects, were well above those associated with serious damage to the head. However, no quantitative studies involving heavier nonpenetrating missiles have yet been carried out.

C. Tertiary Blast Effects

1. The Intraspecies Impact Study

To gain some information about biological tolerance to impact with a hard, flat surface wherein the only significant circumstance mitigating the forces involved would be the "cushioning" effects of the animal's own tissues, Richmond et al.,[57] using 455 rodents distributed among 4 species, determined the impact velocity associated with various levels of lethality.

TABLE 44

EFFECTS OF MISSILE IMPACT ON THE CHEST [12]

Biological effects observed	Threshold velocities for missiles of indicated weights, ft/sec 0.8 lb	0.4 lb
Lung hemorrhages:*		
Side of impact only (unilateral)	45	80
Impact side and opposite side (bilateral)	110	125
Rib fracture*	60	120
Internal lacerations from fractured ribs*	90	120
Fatality within 1 hr*	155	170

*Unpublished data from dogs, AEC Project, Lovelace Foundation, Albuquerque, N. Mex.

In each experiment, ventral impact at 90° with a flat, concrete surface was arranged. From the data obtained, the impact velocity associated with 50-per cent lethality, the V_{50}, was computed along with the probit curve for each species. The V_{50} values were plotted against body weight, a regression curve fitted, and a predicted V_{50} for the 70-kg mammal of 26.2 ft per second (18 mph) was read from the plot shown here as Figure 92.

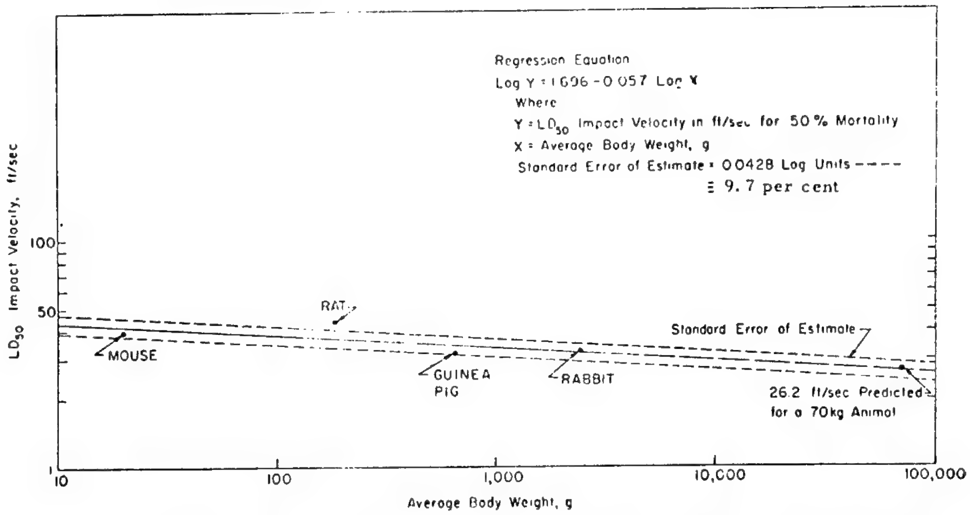
The slope constants of the probit curves were treated in like manner as shown in Figure 93. Using the value obtained by extrapolation to the 70-kg animal along with the V_{50} value of 26.2 ft per second mentioned above, a predicted probit curve was derived for the 70-kg animal as shown by the dotted line included in the left portion of Figure 94. This curve forms the basis for the impact-velocity figures of 20, 26 and 30 ft per second included as tentative criteria for man in the bottom portion of Table 23 labeled "Total Body Impact." Since the data, strictly speaking, apply to ventral impact with a flat, hard surface, one not only wonders how representative the criteria are for similar exposures, but how much variation might be found if the position at impact were randomized. Though there are no clear-cut answers to these questions, a few data exist that are relevant.

2. Automobile Accidents

For example, National Safety Council figures quoted by DeHaven[92] concerning automobile accidents show that "40 per cent of automobile fatalities in urban areas involved a speed of 20 mph or less and 70 per cent were attributed to accidents in which the speed did not exceed 30 mph." This would place the 50-per cent mortality figure near 23 mph (33.8 ft per second) compared with the 18-mph (26.6 ft per second) number derived from the animal impact study. This is not bad agreement in view of the fact that the figures quoted for auto accidents represent estimated vehicular speeds, and not necessarily the velocity with which a fatally injured person struck a solid surface.

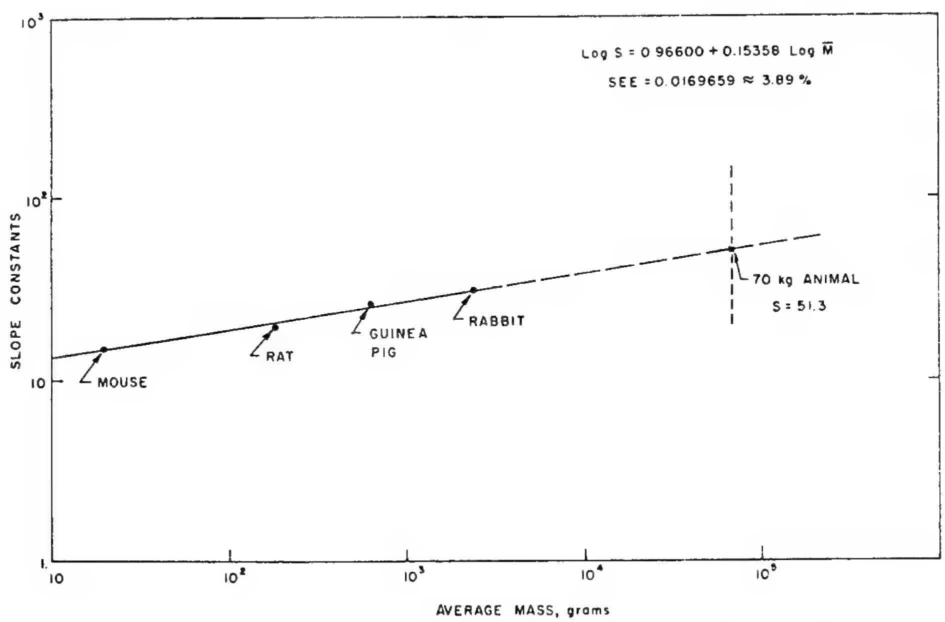
3. Skull Fracture Data

Since head injury is the cause of severe and fatal injuries in



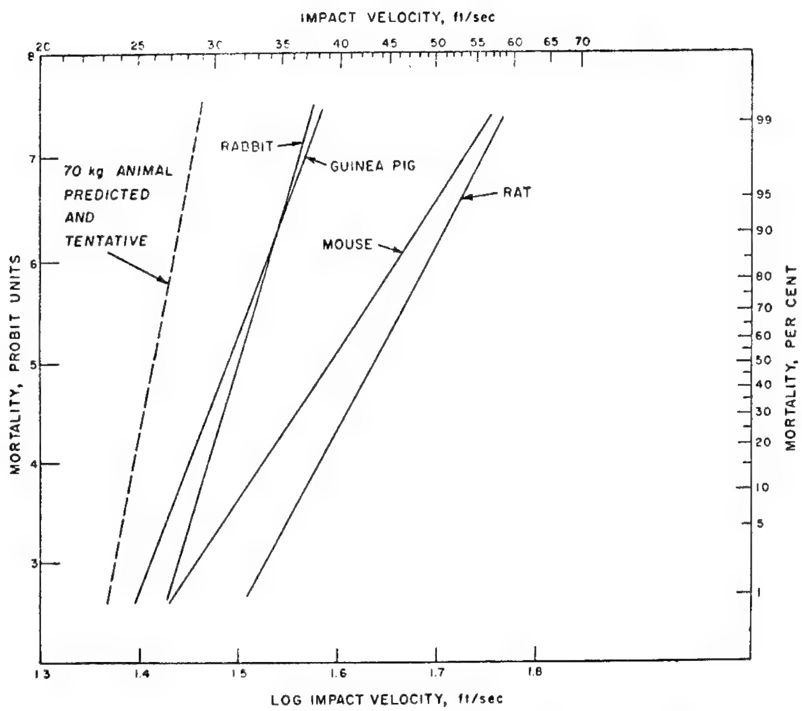
Impact velocity associated with 50 per cent mortality as a function of average body weight. (Ref. 57)

Figure 92



Slope constants of the regression equations relating mortality and impact velocity as a function of animal weight. (Ref. 57)

Figure 93



Comparison of probit mortality curves.[57]

Figure 94

a high percentage of vehicular accidents, it is relevant to call attention to the work of Gurdjian et al.[54] who made impact tests on completely intact cadaver heads. Their data, regrouped to show the percentage of fractures noted as a function of impact velocity, are shown in Table 45. It can be seen that skull fracture, first noted at an impact velocity of 13.5 ft per second (9.2 mph), was present in 50 and 100 per cent of the cases when the impact velocity was around 18 and 23 ft per second (13 and 16 mph), respectively. Though there may be exceptions, such as striking a sharp corner or a head-on impact in an individual traveling horizontally (the head and neck would have to absorb not only the energy inherent in their own motion, but that of the following body as well), it seems reasonable to believe from Table 45 that an impact velocity of 10 ft per second is unlikely to be associated with any, or at most only a few, head injuries. Since this figure is consistent with those of Zuckerman and Black[53] and Drager et al.[58] mentioned previously, the 10-ft per second number along with the data of Gurdjian et al. were included as "skull-fracture" criteria in Table 30.

4. Lower Extremity

World War II experience included many instances of fracture of the calcaneus (heel bone), other bones of the foot, legs, spine and skull associated with sharp, upward motion of the decks of ships caused by detonations below deck or near vessels.[93,94] Such experience stimulated relevant laboratory investigations. A case in point was the experience of Black et al.[59] with embalmed cadavers, dropped stiff-legged with knees "locked" and with the bottoms of the feet made parallel with the floor onto a hard, flat surface from heights of 0.5, 1, 2 and 4 ft. The impact velocity of 11 ft per second associated with the 2-ft drop produced no demonstrable damage. In contrast, that of 16 ft per second occurring from the 4-ft drop caused a complete fracture of the heel bones bilaterally with a "chip fracture" in the posterior surface of each. After a drop of 3 ft with an impact velocity of 13.9 ft per second, a fracture of the left talus bone was noted (the talus lies above the calcaneus or heel bone and separates the latter from the two bones of the lower leg at the ankle) even

TABLE 45

THE RANGES OF IMPACT VELOCITIES ASSOCIATED WITH EXPERIMENTAL FRACTURE OF THE HUMAN SKULL*

			No. of subjects		Fractures per cent	
Impact velocity ft/sec	Approximate velocity mph	Approximate height of fall in.	Grouped	Accumulative	Grouped	Accumulative
13.5 to 14.9	9.5	37	9	9	19	19
15 to 16.9	10.9	48	10	19	22	41
17 to 18.9	12.2	61	12	31	26	67
19 to 20.9	13.6	75	11	42	24	91
21 to 22.9	15.0	91	4	46	9	100
TOTAL			46	46	100	100

*Assembled from the data of Gurdjian et al.[54]
Minimum velocity with fracture, 13.5 ft/sec (9.2 mph)
Maximum velocity with fracture, 22.8 ft/sec (15.5 mph)
Maximum velocity without fracture, unstated.

though special sponge rubber padded boots with strong rubber heels were employed in the test.

In that fractures were observed on an impact table energized with a blow from below delivered by a heavy pendulum at "initial" velocities ranging from about 13 to 21 ft, Drager et al.[58] added reasons for believing that velocities much above 11 - 12 ft per second can indeed cause fractures of the foot and lower extremity.

5. Spine

Ruff[63] in experiments on humans reported 20 G, applied from seat to head for a total impact time of 100 msec, caused headaches, transient, lacinating pain in the region of the dorsal and lumbar vertebra followed by dull neuralgic discomfort in the spinal region that lasted for days and on one occasion included sciatic-like pain in the legs. He estimated these conditions to be close to the fracture limit for man. Ruff also stated the static load required to fracture adult dorsal and lumbar vertebra ranged from 1322 - 1988 and 1760 - 2644 lb, respectively. In a more recent study, Perey[95] reported 43 per cent of vertebra studied were fractured by 620 kp (1364 lb) while dynamic fractures were connected with 1200 kp (2640 lb).

Gagge and Shaw[96] placed acceptable conditions for ejection seats at 20 G developing at the rate of 150 G per second and enduring for 200 msec. Watts et al.[97] reported that 20 G for 80 msec applied at the rate of 200 G per second produced no symptoms in 50 volunteer Naval subjects.

The data regarding tolerance of the spine noted above are consistent with the criteria noted in Table 30 and the diagram of Hirsch shown in the lower half of Figure 71.

6. Falls and Other General Data

That human tolerance to decelerative loading is extremely sensitive to stopping time and distance is illustrated by the analysis reported by DeHaven[98] of falls from 55,* 93 and 145 ft. Impact velocities ranged from near 60 to about 85 ft per second, the stopping distances from about 0.3 to

0.7 ft, and the deceleration time from 0.01 to 0.02 seconds.

The DeHaven data along with "ball park" parameters concerning parachute opening and landing shocks, catapults, ejection seats, auto and racing accidents were assembled by Roth[91] in an informative illustration, reproduced here as Figure 95. The figure delineates velocity-distance-time-acceleration relationships as they apply to accelerative and decelerative tolerance in man.

7. Shock Motion Studies of Hirsch

Hirsch,[61] in an excellent recent study, subjected human volunteers to changes in velocities ranging from 8 to 10 ft per second over times varying from 0.5 to 19 msec on a ship-shock simulator. Average accelerations were from about 16 to 24 G. Subjects experienced "considerable discomfort and complained of sore heels and pains in the back and pit of the stomach, but suffered no injuries." Because the analytical work was highly informative, Figures 5, 6, 10 and 11 from the paper of Hirsch are reproduced here as Figure 96.

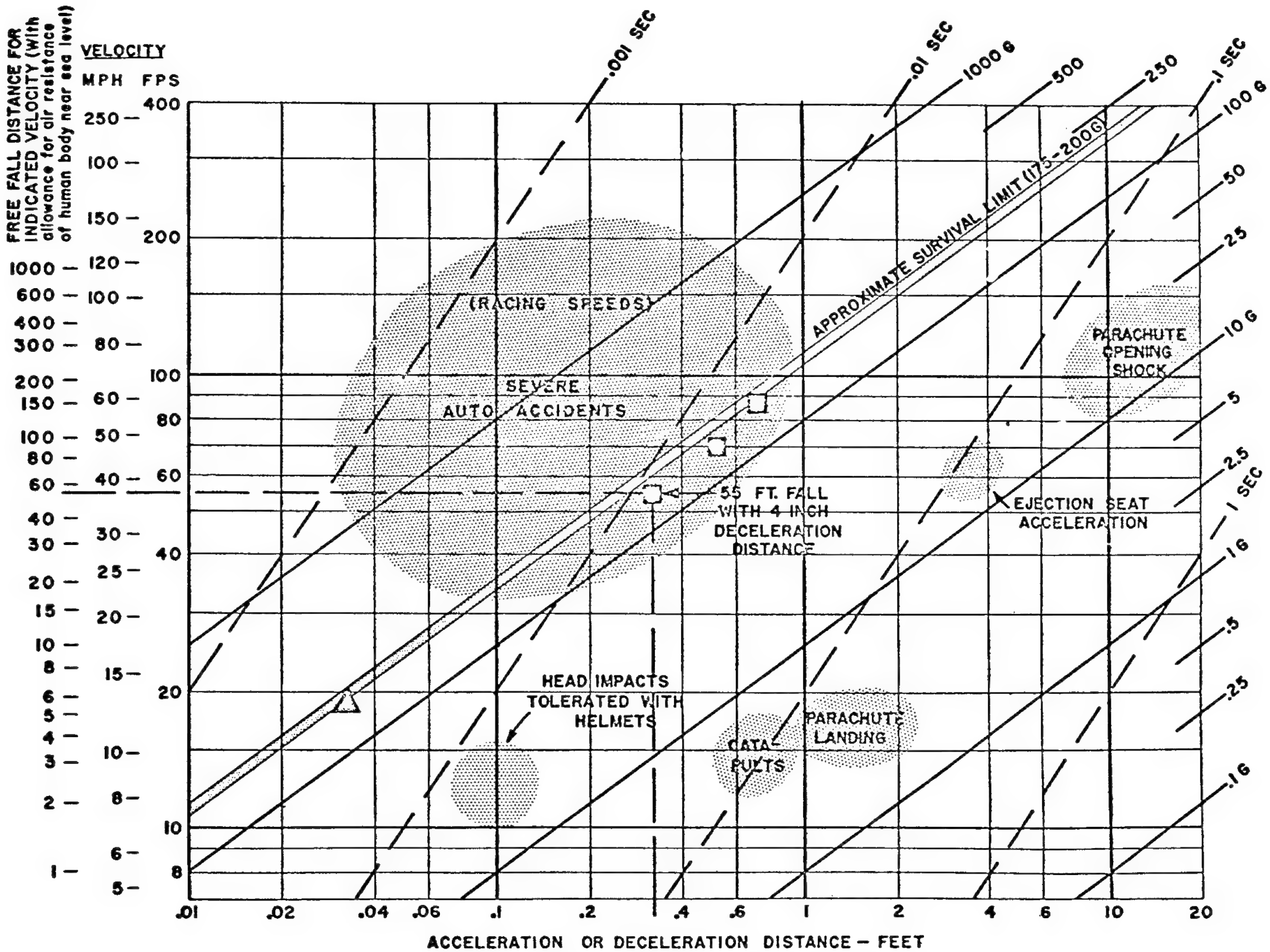
On the left-hand side of Figure 96, displacement-time diagrams, showing the upward motion of the simulator and appropriate portions of the bodies of seated and standing, unrestrained subjects, indicate that the individual initially underwent a compressive experience after which he was thrown away from the deck with a "kick-off" velocity determined to be about 60 to 120 per cent of the peak velocity of the deck of the shock motion simulator.

Because the "kick-off" velocity might well help determine the magnitude of a subsequent decelerative hazard, the empirical equation derived by Hirsch for quantitating the velocity is set forth below:

$$V_k / V_d = 2.7 \, (t_p / T)^{0.44}$$

where V_k = "kick-off" velocity; V_d = peak deck velocity; t_p = rise time to peak deck velocity; and T = the natural period of man.

The upper, right-hand portion of Figure 96 shows information from which Hirsch deduced natural periods for man applicable to exposures on the shock-motion simulator. Thus, "T" in the equation above can be taken

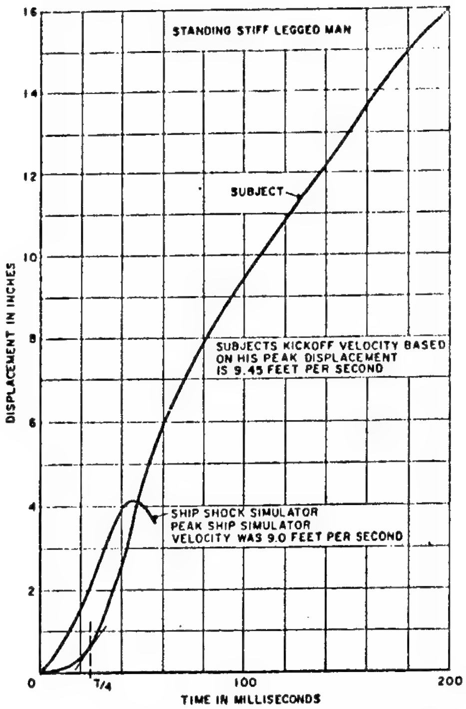


Velocity - Distance - Time - Acceleration Chart

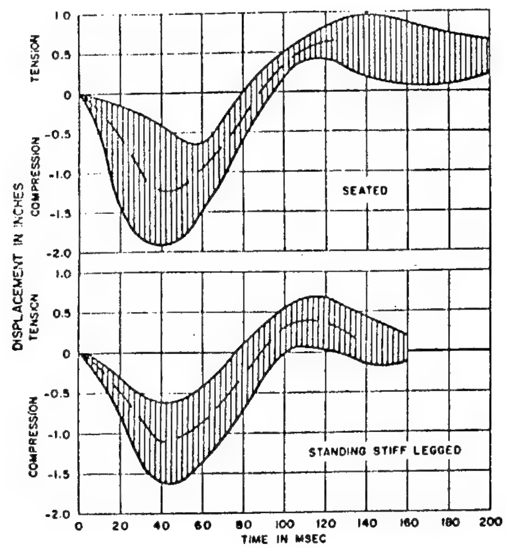
Survived falls shown by squares. Triangle represents Cornell University estimate of deceleration of human head experienced in a fall from standing position with the head hitting a hard surface.

Reproduced from Roth[91]

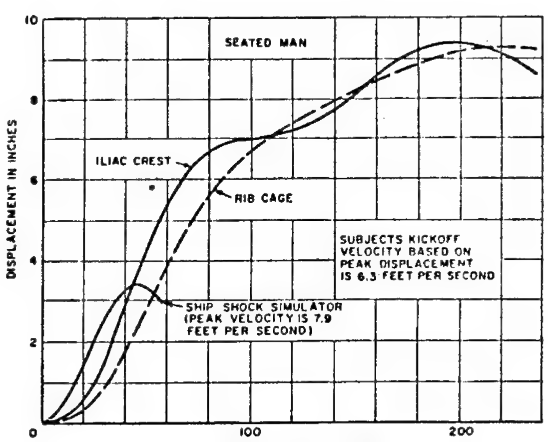
Figure 95



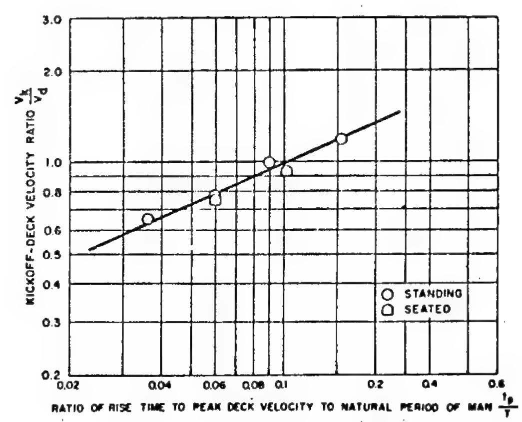
Displacement of center of gravity of standing man (measured at crest of iliac) and ship shock simulator during test 11, shot 72 [61]



Envelopes of displacement of rib cage toward iliac crest during exposures of volunteers to short-duration shocks of varying intensities [61]



Displacement of center of gravity (iliac crest), rib cage and ship shock simulator during Test 9, shot 141 on seated subject [61]



Ratio of kickoff to peak deck velocity as a function of ratio of rise time to peak deck velocity to natural period of man [61]

Reproduced from Hirsch[61]

Figure 96

to be 100 msec for standing man and 167 msec for seated man.[61]

The lower, right portion of Figure 96 shows a plot of the ratio of the "kick off" to peak deck velocity (V_k/V_d) as a function of the ratio of the time to peak velocity to the natural period of man (t_p/T). The diagram makes it clear that the data for both seated and standing subjects are quite consistent with one another.

8. Impact Studies of Swearingen

Swearingen et al.,[60, 66] working with 13 human volunteers, reported nearly 500 separate experiments in which subjects were dropped, either standing or sitting in a track-guided chair, against a platform mounted on heavy springs and damped with hydraulic pistons. Though the platform was capable of moving one inch, the actual motion in the tests was not recorded, but it was known to be small. G-time recordings were made when standing individuals with knees "locked" were dropped from a maximal height of 2 ft. Though the theoretical velocity from this fall height is 11.3 ft per second, it is likely that the actual impact velocity ranged from 8 - 10 ft per second and deceleration occurred in a time period of around 8 msec. The G curve showed a maximum of 65 developing at 10,000 G per second and enduring for 8 msec. This loading was the maximum tolerated by any of the subjects who reported severe pain in the chest, epigastrium, lower back, hip joints, top of the head, arches of the feet, back of the legs, ankles, heels and throat.

In drops with seated subjects, the voluntary tolerance limit was placed at 95 G developing at a rate of 19,000 G per second over a time period of 7.5 msec. It is probable the maximum velocity change was between 9 and 11 ft per second, but the exact figure is not known. Subjects complained of severe pain in the chest, spine, head and stomach and "shock: severe, general" was reported.

9. Comment

The eight sections immediately above set forth the background data from which the tentative tertiary blast criteria included in Table 30 were developed. That the criteria are incomplete should be emphasized at least

for five reasons; namely,

First, because of the lack of quantitative data for blows over the spleen, liver and abdominal wall, generally.

Second, because as Hadden and McFarland[99] have pointed out in a competent review of the present knowledge concerning head injury, no data are at hand for infants, children and adolescents at one end of the age scale nor for those in the last decades of life on the other.

Third, the role of position or orientation at impact as it influences the "self-cushioning" function of the body in protecting critical organs from grave or fatal injury upon impact with hard surfaces is far from well understood.

Fourth, the fact that increases in stopping time and distance are associated with increased tolerance to impact, expressed in terms of velocity at impact, continues to be confused with the "self-cushioning" action of the body itself and, while this may be because definitive data are lacking, the difficulty is also likely to be conceptual in nature.

Fifth, the causes of impact lethality needs better definition[57, 100] to help segregate innate variability in response from what in reality is a variation due to differences in "load" on critical portions and organs of the body.

Also, the five reasons mentioned above bear upon the tentative nature of the tertiary blast criteria, which as time goes on, will be refined and extended to fill the gap between tolerance to impact with "hard" surfaces on the one hand and "soft" ones on the other. This means that the pioneering studies by Stapp using rocket sleds to investigate decelerative forces in human subjects[101, 102] and the recent work of Aldman[103] also contributing to the understanding of impact protection and the role played by the differential displacement of different parts of the body under decelerative loading with various restraints — both representing tolerance to relatively "high"-velocity changes occurring over relatively "long" periods of time — will be conceptually integrated with studies similar to those of Richmond et al.,[57] Hirsch[61] and Swearingen et al.[60, 66] — all

dealing with tolerance to relatively "low"-velocity changes occurring over relatively "short" periods of time.

Finally, the synthesis of understanding, already partly under way by Goldman and von Gierke[104] and by Kornhauser,[105] will come to include both the work of Snyder[106, 107] on human survival after free falls and the data of Lombard et al.[108, 109] and Thiede et al.,[110] whose investigations on tolerance using carefully restrained animals subjected to lethal velocity changes over very short periods of time carry thinking about impact and the damage suffered therefrom into a region that is close to or actually overlaps that of air blast itself.

D. Translational Scaling

Understanding the environmental variations that occur inside protective shelters — closed or open, but particularly the latter — requires that one adequately carry out free-field, geometric and translational scaling.[2, 11, 14, 29-31] The first allows one to estimate the major effects parameters over near-flat terrain as a function at least of explosive yield, design, burst conditions, range and weather. Geometric scaling allows the free-field parameters to be modified as is appropriate to the conditions or geometry of exposure. Translational scaling helps establish the effects of energy interchange whereby movable objects are translated as a consequence of variations in certain local environmental conditions.

Some progress has been made in the area of translational scaling for objects as small as slivers of window glass and as large as man for conditions in the open and to some extent in houses when blast winds associated with typical or near-typical wave forms are involved.[21,51, 111-115] Also, it is appreciated that translational hazards inside open protective structures due to blast-induced winds are likely to be maximal in openings and entryways wherein high-velocity wind jets funnel into the interior portions of a shelter, and minimal at locations against a wall normal to the advancing pressure pulse, in which regions "stagnation" pressures develop and winds are near zero. Though it is possible to investigate these two extremes (and conditions in between) empirically and theoretically, only the minimal condition mentioned above has been given some study locally.

In what follows, results from the latter will be described after a few summarizing statements about the "state of the art" in translational scaling are presented.

1. The Bowen Translational Model

Using experience gained at the Nevada Test Site with over 20,000 objects translated by blast pressures and winds,[21, 51, 111] — among them anthropometric dummies,[112] steel spheres and weighted croquet balls simulating man,[21, 51] — a mathematical model was developed by Bowen et al.[113] for typical or near-typical wave forms to predict the velocity-mass-distance-time relationships for objects of different acceleration coefficients,[114] α.* For example, note from Figure 97 that stone missiles of different masses exposed at 5 psi from a 10-kt detonation at Nevada altitude, approach and reach the associated wind velocity at different times after arrival of the shock. During this time, each missile would travel finite distances over which velocity would increase to a maximum.

A second example, involving the exposure of a 165-lb anthropometric dummy back-on (α = 0.052 ft^2/lb) to a 5 psi pulse during the 1957 Nevada test operation,[112] is shown in Figure 98[113] from which it can be seen that the dummy attained a maximal velocity of 21 - 22 ft per second in about 0.5 second after traveling slightly more than 8 ft. At the top of Figure 98 the changing position of the dummy during translation is illustrated. The dotted lines in the figure are computed velocity-time-distance relationships predicted for different positions of the dummy, assuming that the latter did not change during translation.

To illustrate the level of agreement between empirical and predicted data, Figure 99 was prepared. The dotted or predicted curves were computed using the acceleration coefficients (α's) that were required for the different positions of the dummy diagrammed at the top of Figure 98.

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*The acceleration coefficient, $\alpha = \frac{A}{m} \cdot C_d$ where A = area presented to the wind, m = mass and C_d = drag coefficient for a displaced object, was determined in the laboratory for various objects and animals by Fletcher et al.[114]

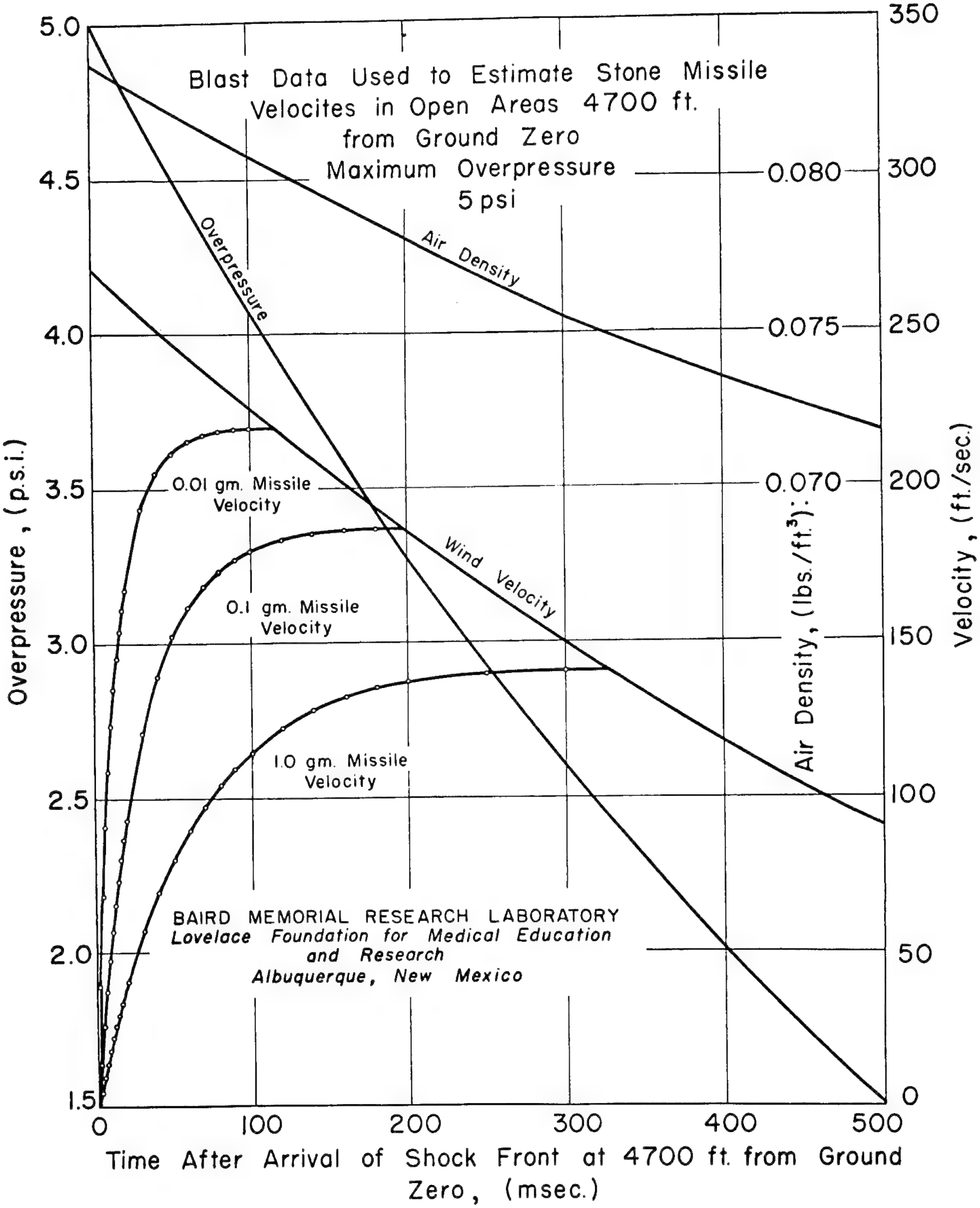


Figure 97

After Bowen et al., WT-1168[111]

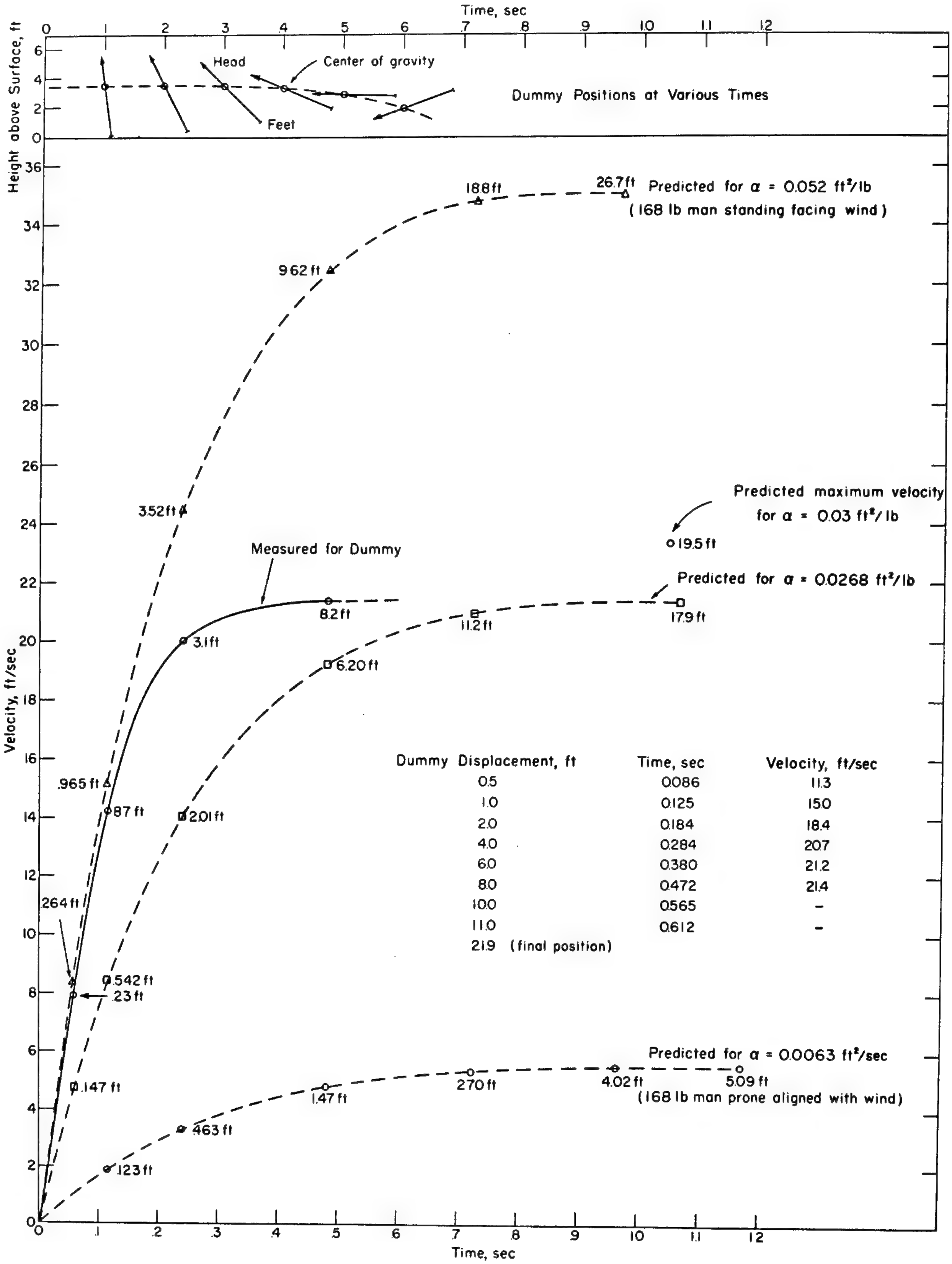


Figure 98

After Bowen et al., CEX 58.9 [113]

ANALYSIS OF DUMMY DISPLACEMENT, SHOT I

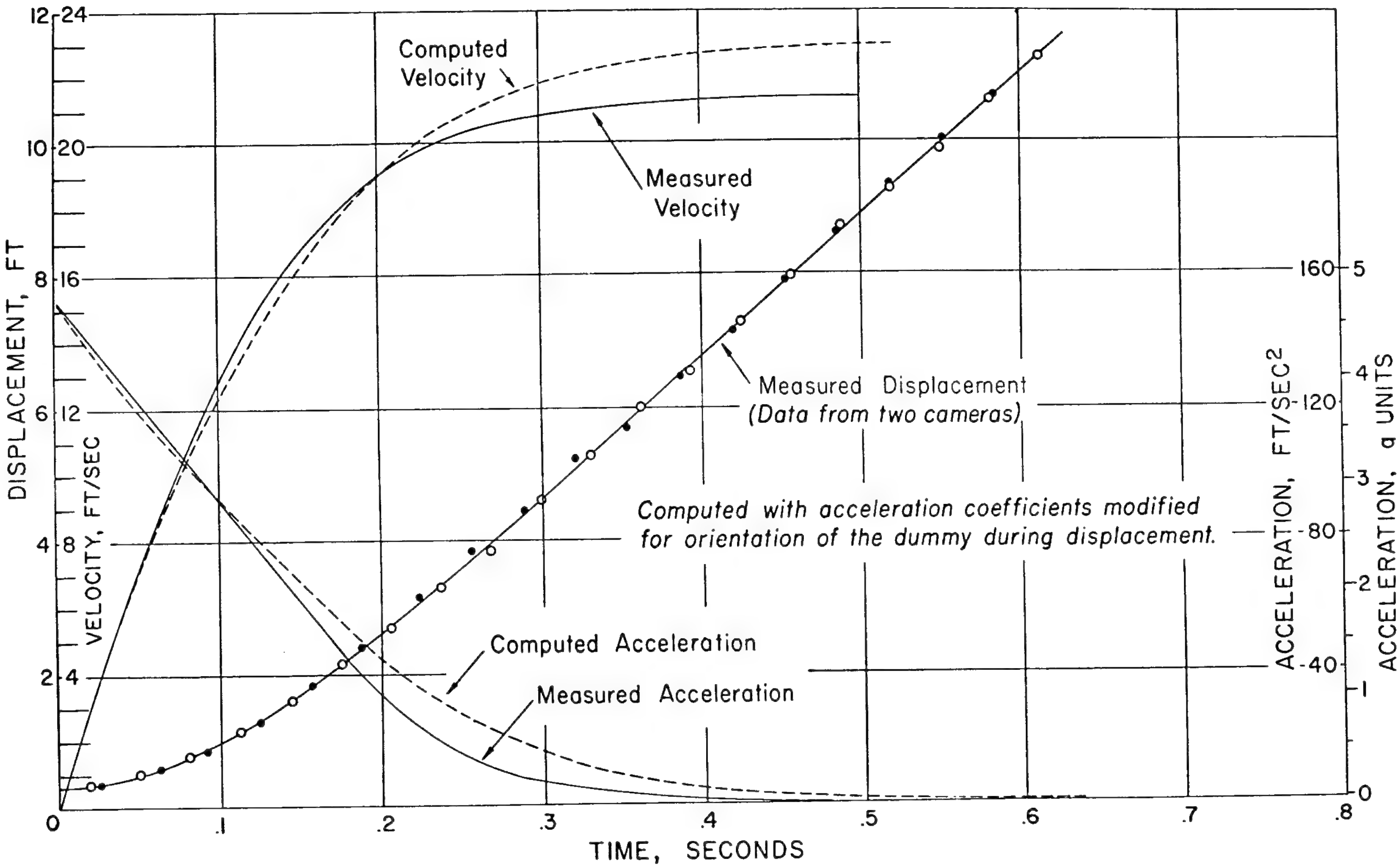


Figure 99

Reproduced from DASA 1271[29]

Thus, for clean wave forms at least it has become possible to calculate and predict translational velocities as a function of appropriate parameters. Figure 100 shows one such result for objects having various α's plotted against maximal translational velocity if exposure at from 3 to 14 psi occurred at Nevada altitude from a 10-kt typical air burst. Also, Figure 101 gives velocity <u>at 10 ft of travel</u> as a function of scaled range predicted for man and window-glass fragments energized by surface bursts or those chosen to maximize (optimize) the velocity — and hence the overpressure — at a given range.[115]

2. <u>Impact Velocity and Initial Distance from a Reflecting Surface</u>

Because exposure against a reflecting surface is likely to maximize primary blast hazards and at the same time minimize those due to translation, whereas exposure away from the reflecting surface could maximize translational dangers and minimize those associated with the pressure pulse, it is of interest to examine a relevant special case applicable to inhabited but "open" protective structures using analytical methods similar to those employed in formulating the translational model of Bowen.

<u>The Geometry of Exposure</u>

To approach the problem several assumptions were made; namely,

a. That the blast overpressures and winds moved toward a shelter wall placed normal to the advancing pulse (as is the case near the end of a shock tube closed by a plate bolted across the tube).

b. That an individual was exposed at various distances up to 20 ft in front of the reflecting wall in three different orientations, each remaining constant during translation; viz., (1) standing face or back-on (broadside) to the wind (α = 0.052 ft^2/lb); (2) prone aligned with the wind (α = 0.0063 ft^2/lb) and crouching broadside, standing

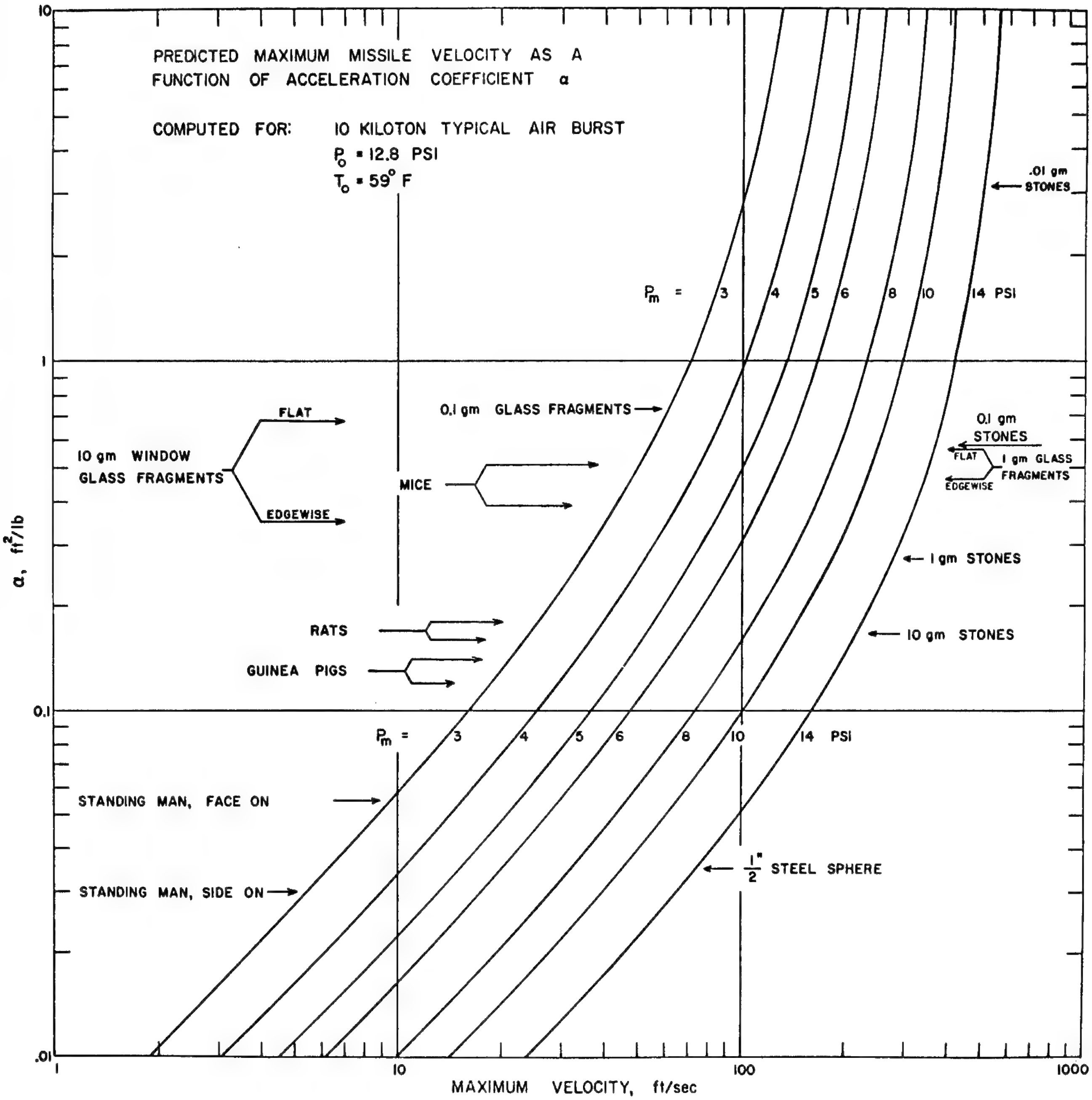
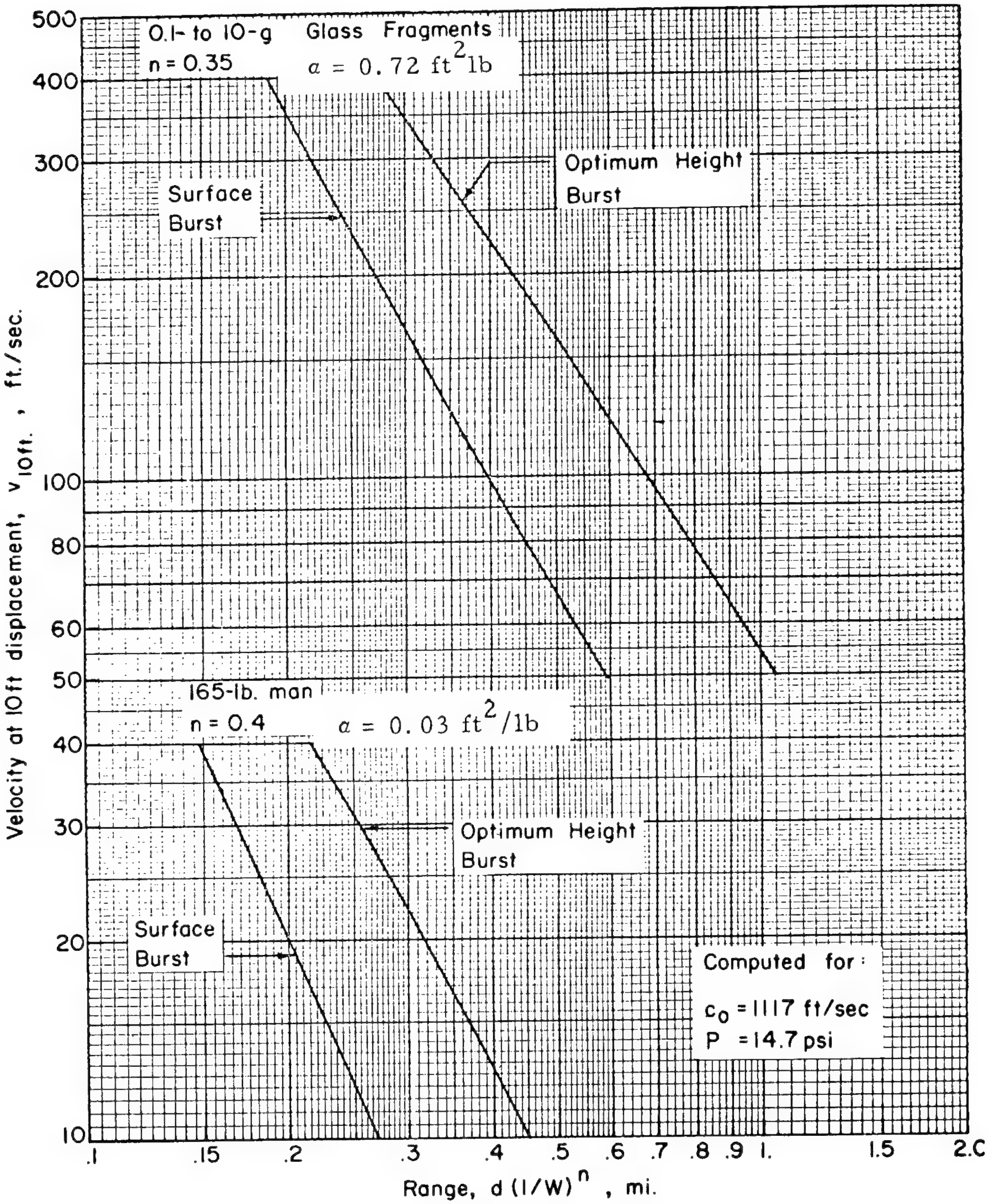


Figure 100
Reproduced from DASA 1271[29]



Velocity of man or window glass at a 10-ft displacement for surface bursts or optimum heights of burst as a function of scaled range (after Fletcher et al., CEX-62.2[115])

Figure 101

sidewise or prone perpendicular to the wind (α = 0.0021 ft^2/lb).

c. That the frictional forces of the moving object with the shelter floor were negligible, the incident blast wave was "shocked" and the overpressure of the incident wave remained constant as long as it might influence the motion of the translated individual.

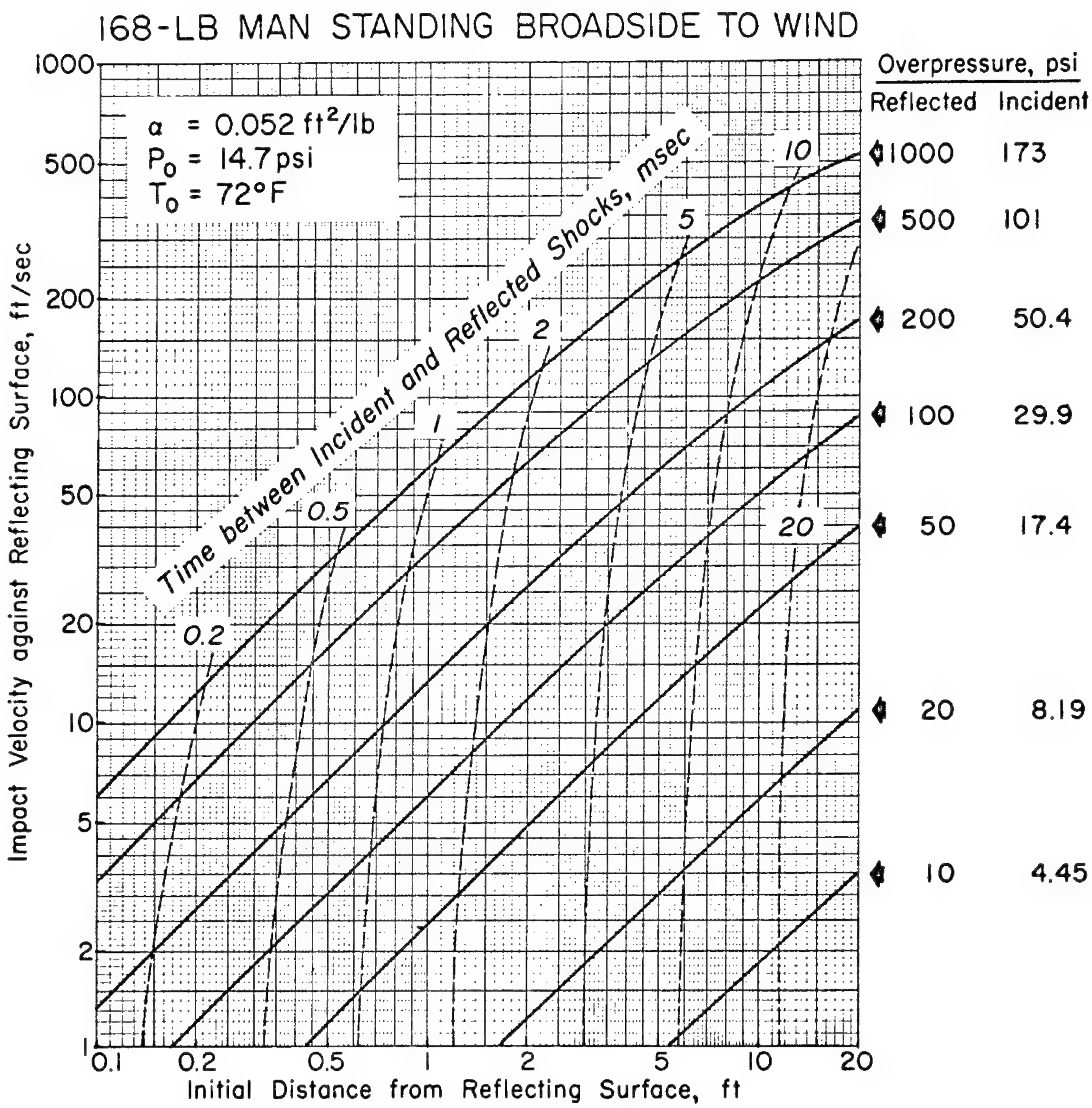
d. That the translated individual was accelerated by the constant winds behind the "square-wave" pressure pulse of the incident shock until the arrival of the reflected wave at the new position of the person, after which the target was allowed to decelerate until reaching the wall because of its motion through the quiet, but dense air behind the reflected shock.

The Impact Velocity-Distance-Pressure-Time Relationships

The computational results,* set forth in Figures 102, 103 and 104, show the predicted impact velocities as a function of the initial distance from the reflecting surface.[116] Each solid line corresponds to a blast wave identified by the indicated incident and reflected overpressures. The dashed lines specify the time after which the incident wave passes the object until the reflecting wave reaches it; i. e., the duration of the accelerative phase of displacement. Perusal of the figures, particularly if the criteria for assessing primary and tertiary blast hazards are kept in mind, is of interest for a variety of reasons. Four, among them, will be mentioned here.

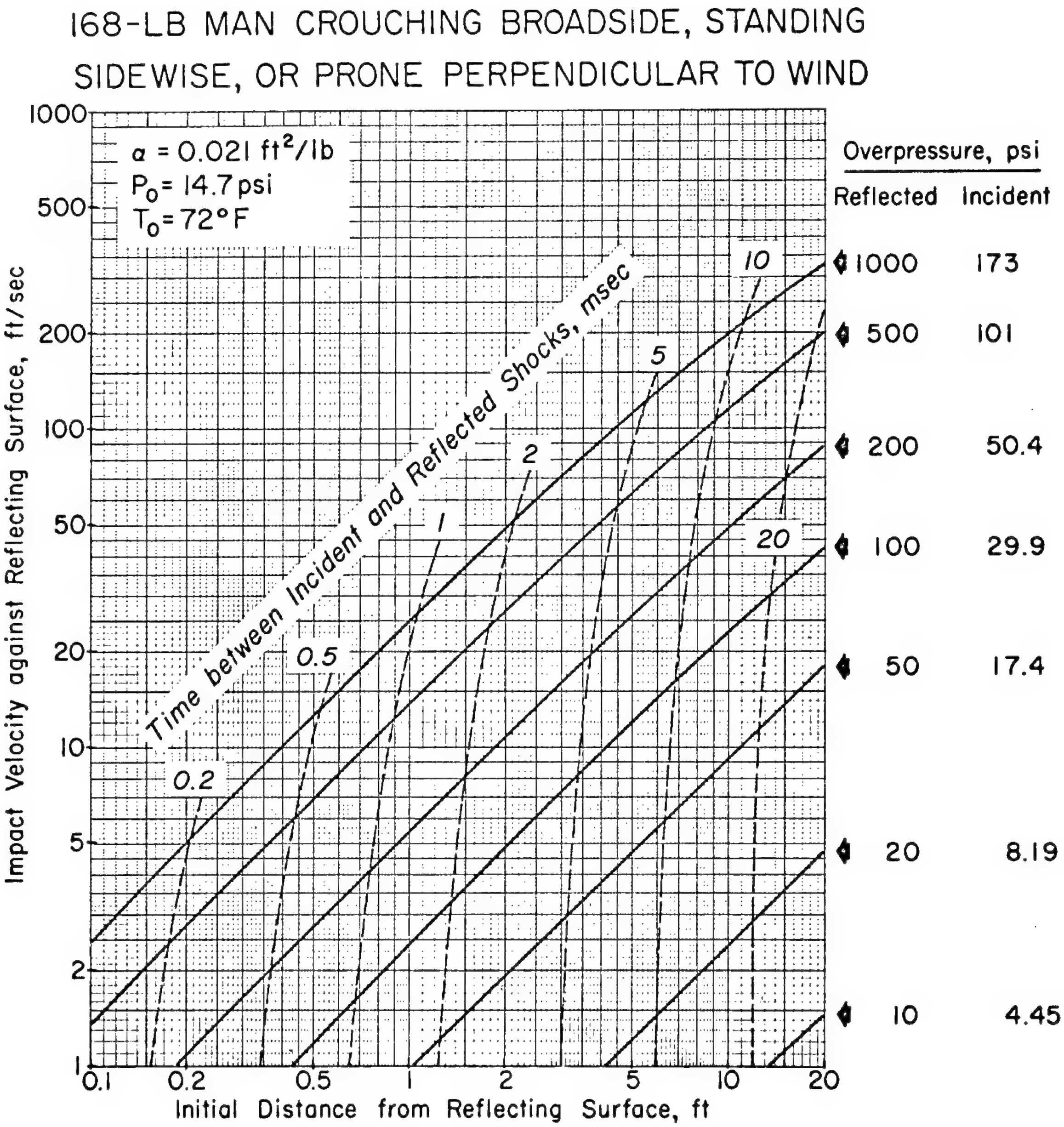
First, to illustrate the type of information that is revealed by the computations described, an example involving Figure 102 will be

*Dr. E. R. Fletcher, Physics Department, Lovelace Foundation, was kind enough to carry out the required analytical work and supervise the computations to obtain data from which Figures 102, 103 and 104 were prepared.[116]



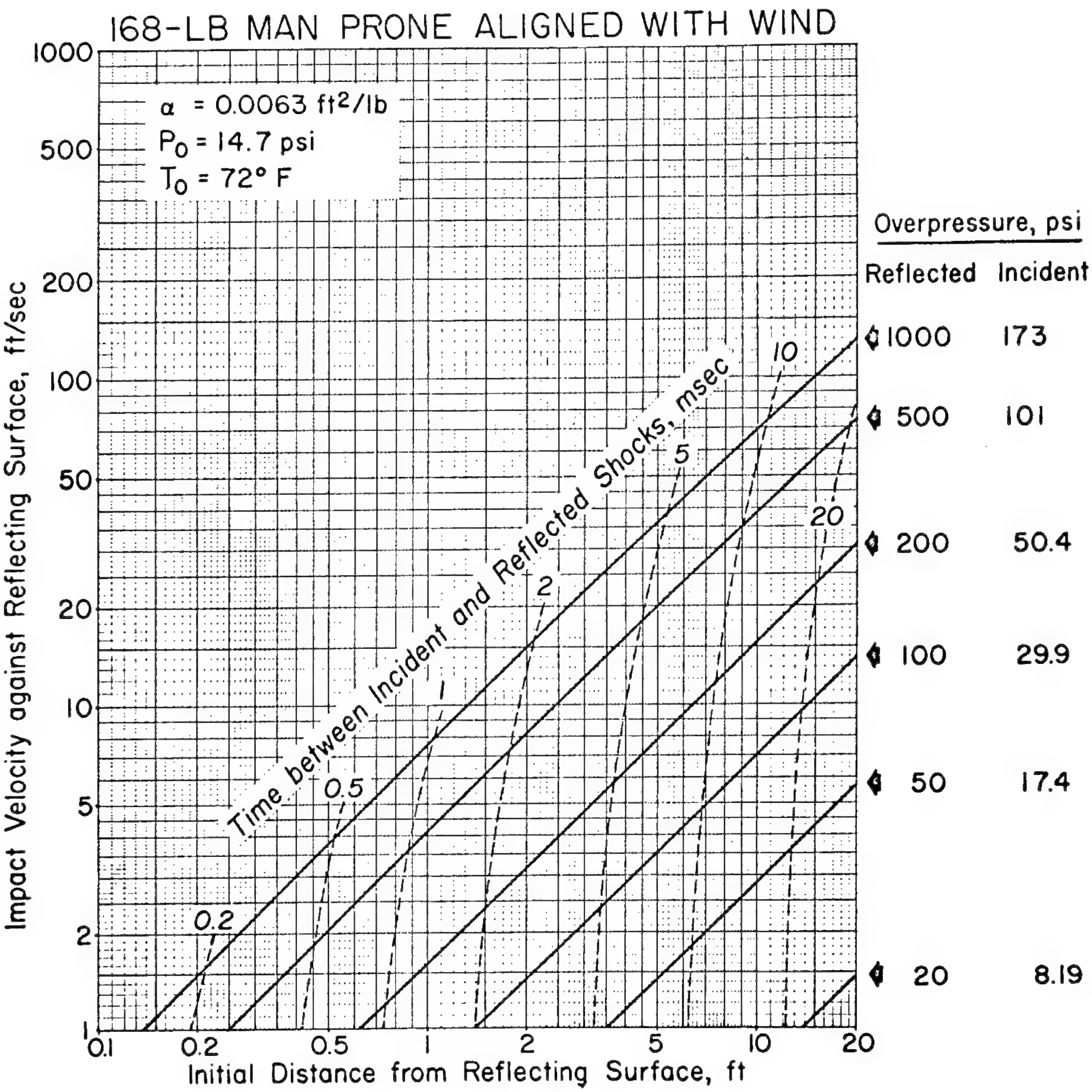
The impact velocity predicted for man standing at the indicated distances from a wall and exposed at normal incidence to various incident and associated reflected overpressures.[116]

Figure 102



The impact velocity predicted for man assuming the specified positions at the indicated distances from a wall and exposed to various incident and associated reflected overpressures.[116]

Figure 103



The impact velocity predicted for prone man located at the indicated distances from a wall and exposed aligned with the wind to various incident and associated reflected overpressures.[116]

Figure 104

cited. Consider a 168-lb man standing 10 ft from a reflecting wall facing the winds accompanying a square-shaped (shocked) blast wave of about 30 psi overpressure advancing from the entryway of the shelter. The figure shows that the man would be accelerated in about 14 msec to a velocity of almost 50 ft per second neglecting the reduction in velocity during the decelerative phase. The average acceleration would be 50/.014 = 3600 ft/sec^2 or 110 G units. The average velocity of the man during acceleration would be 50/2 = 25 ft/sec (the individual's velocity would always be small compared with that of the wind) and the distance he would travel before encountering the reflected shock would be about 25 ft/sec x 0.014 sec = 0.35 ft. Again assuming a negligible velocity loss while traveling through the quiet air behind the reflected wave, the required time for the man to reach the wall would be (10 - 0.35) ft/ (50 ft/sec) = 0.193 sec. Thus, the total travel time would be 193 + 14 = 207 msec. Of course, if the overpressure in the incident wave should decrease in less than 207 msec, the air in the reflected shock would begin to move away from the wall, tending to reduce the man's velocity towards the wall.

Second, if pressures inside a structure were held to a maximum of 10 psi reflected and thus were below the level thought to damage the lung even for those exposed against a reflecting surface, predicted impact velocities might be as high as 3.5 ft per second for individuals located as far as 20 ft from a wall. Thus, except for a person situated in or near any high-velocity winds in an entryway, the translational hazard, as well as the pressure hazard, would be insignificant.

Third, however, consider exposure 4.2 ft from a wall to an incident pulse of 17.4 psi. From Figure 102 and Table 30, one can estimate that the predicted impact velocity of 10 ft per second would not be hazardous and appreciate that about 6 - 7 msec after the incident wave of near 17 psi passes the target, the reflected pulse of close to 50 psi would arrive. Now from Table 28, it can be noted that 50 psi applied "rapidly" would likely be lethal to 50 per cent of individuals exposed. To the contrary, judging from small animal work noted in Table 36 and Figure 84, a stepwise increase in overpressure is likely to be nonlethal even if the

P_{max} is well above the 50-per cent lethal pressure for "fast"-rising pulses providing the time step between the two pulses is sufficiently long. While this is also probably true for large animals including man, it is unfortunate that definitive quantitative data are currently unavailable.

Thus, the example cited illustrates one practical need for criteria applying to overpressures increasing in two "fast" steps to help assess the optimal position for exposure in open, protective structures.

Fourth, imagine exposure 4.6 ft from the wall of a shelter, hit at 90° by an incident, "fast"-rising pulse of 30 psi, a pressure likely to be just near the lethal range for human adults (see Table 28). From Figure 102, it can be determined that the predicted impact velocity for standing man under these conditions would be about 26 ft per second, likely to be associated with 50-per cent lethality from "whole-body" impact (see Table 30). This situation just cited poses at least one important question; namely, what would lethality be for the combined challenge of exposure first to the 30 psi incident followed in 6 - 7 msec by the 100-psi reflected shocks, and, second, to violent impact with the wall at a velocity near 26 ft per second?

Again, a relatively simple practical question cannot be answered definitively because there are no criteria for combined injury that are applicable to primary blast plus impact, nor for that matter, to few other combinations of the major nuclear effects that might challenge man.

E. Combined Effects

The statement just made should not mean that there are no data available that apply to combined injury. Though some information indicating synergism between two effects is at hand — for example, Brooks et al.[117] demonstrated over a sixfold increase in lethality (12 to 73 per cent) from a standard burn in dogs when 100 r of total body gamma radiation, producing no lethality when administered by itself, was given as an additional stress — it is nonetheless true that quantitative studies of integrated (combined) effects are insufficient to allow appropriate and reliable criteria to be formulated.

Since reviewing the literature to assess the "state of the art" in combined stress is a somewhat time-consuming exercise, it is hardly considered appropriate for this communication. Suffice it to say here that while the general and specific problems are involved and complex, there is a great need for effective research programs in this area.

V. DISCUSSION

By way of discussion, a few remarks regarding the three main sections of this paper seem indicated. They are set forth below.

A. Blast-Related Problems in Shelters

The Nevada shelter data, presented above to help illustrate the nature of blast-related problems of interest to the designers of protective shelters, are significant for a number of additional reasons. Among them are the following.

First, those wanting to know about marginal or threshold conditions for damage should appreciate that, meager as it is, the Nevada field work incorporates by far most of the biological information that exists concerning exposure to blast-induced changes in the environment at levels near those for minimal hazards that are referable both to shelters and nuclear explosions.

Second, no laboratory experiments to date employing disturbed wave forms have used animals in numbers that approach those exposed in Nevada to such waves. This is not because of inability to simulate the general shape of the pressure pulse in the laboratory, but rather to the fact that higher priorities were placed on the need to understand the effects of "fast"-rising pressures which produce lethality at lower maximum overpressures.

Third, the Nevada projects serve to emphasize the major importance of exposure conditions, which can sharply enhance, minimize or eliminate hazards that might otherwise exist for exposure to the free-field blast waves at the same range; i.e., the geometry of exposure emerges as a major factor to be considered not only in assessing the biological effects of nuclear weapons, but in planning protection as well.

Fourth, the results with biological media exposed in "open" structures in Nevada illustrate very well the hazards from (a) violent displacement; (b) penetrating and nonpenetrating missiles, arising either outside or inside the structure and energized by wind, ground shock and gravity; (c) non-line-of-site thermal phenomena; and (d) overpressure, particularly if fast-transient reflections occur.

Fifth, while serving on the one hand to emphasize potential hazards, experience with "open" structures makes it clear on the other hand that at certain locations inside the shelter, survivability is not only possible, but highly probable compared with what would have occurred if exposure had been in the open at the same range.

Sixth, shelters tested "open" were found postshot to be littered with a great deal of debris, dirt and dust, some of it radioactive; they certainly left much to be desired from the point of livability, a factor that deserves much attention in protective design if occupancy is planned for more than a few hours and days.

Seventh, though the writers confess a prejudice for "closed" protective structures, it must be said in all fairness that what were tested in Nevada as an "open" structure were emphatically not designed to function optimally as "open" shelters. The latter avenue deserves exploration using theoretical and computational techniques available today along with empirical ones employing shock tubes and models. It could very well be that it would cost more to design and build an adequate "open" structure than a "closed" one, but then the opposite might turn out to be true.

Even so and eighth, let it be clear that the designer of an "open" structure, advertised as a protective shelter, faces a difficult task including the burden of proof regarding adequacy in view of the several serious hazards that none should fail to appreciate.

Ninth, regarding "closed" shelters, there can be little doubt that (a) gross and component movement of the structure can pose hazards to personnel, (b) that for planning purposes the initial movement of a structure in any direction can be thought possible, and (c) that a few common-sense measures could minimize or eliminate danger to occupants: e.g., using

energy-absorbing material, such as Ensolite, where indicated on the floor, walls and ceiling; using "flush-with-the-surface" design approach, avoiding sharp corners and edges, and padding those that emerge in the final product; making sure all equipment is securely anchored; encouraging the installation of shock-mounted seats equipped with seat belts and shoulder harness at selected work stations; and supplying and requiring the use of helmets to help protect the head.

Tenth, concerning the dust problems in "closed" shelters, there seems to be no reason to doubt that particulates did spall from the walls and ceilings of the Nevada shelters, that a condition somewhat like a dust storm suddenly developed inside the structures postshot and that a high percentage of the particulates were in the respirable range. Whether or not dust also entered the shelters through the sand traps guarding the inlet of the ventilation system cannot be stated with certainty. However, this is a distinct possibility and could have contributed to the differences noted in the particle-size distributions for the samples of postshot and and pre-plus-postshot dust. The variability noted could have been due to damage to the air-inlet shaft and to different amounts of preshot dirt in the several portions of the air-inlet passage ways.

Also relevant to the discussion, though not mentioned previously in the text, were the postshot samples of dust recovered from the concrete-arch and conduit shelters noted in Table 23. All were reasonably and consistently similar to one another. This means one of three things: (a) that most of what appeared on the sticky papers arose postshot from the walls of the structure (most likely); (b) that the dust samples arose from the floor <u>and</u> the walls, the preshot contamination from the floor being minimal or (c) that only preshot floor dirt was involved, providing the preshot contamination of the "control" side of the tray was very slight.

Eleventh, several possibilities for eliminating or minimizing annoyance or hazards from dust in "closed" shelters seem quite practical. Among them are the use of a heavy-base paint on the interior surfaces of concrete shelters to help avoid spalling of small particles; the use of appropriate binders in concrete to help keep particulates "large" and above the respirable range in case of cracking and gross spalling; the avoidance of

filling defects of inner surfaces with mortar; prohibiting the plastering or mortar dressing of internal walls of structures; employing metal or other appropriate liners for concrete protective shelters; and construction of shelters with metal rather than frangible materials.

B. Criteria for Hazards Assessment

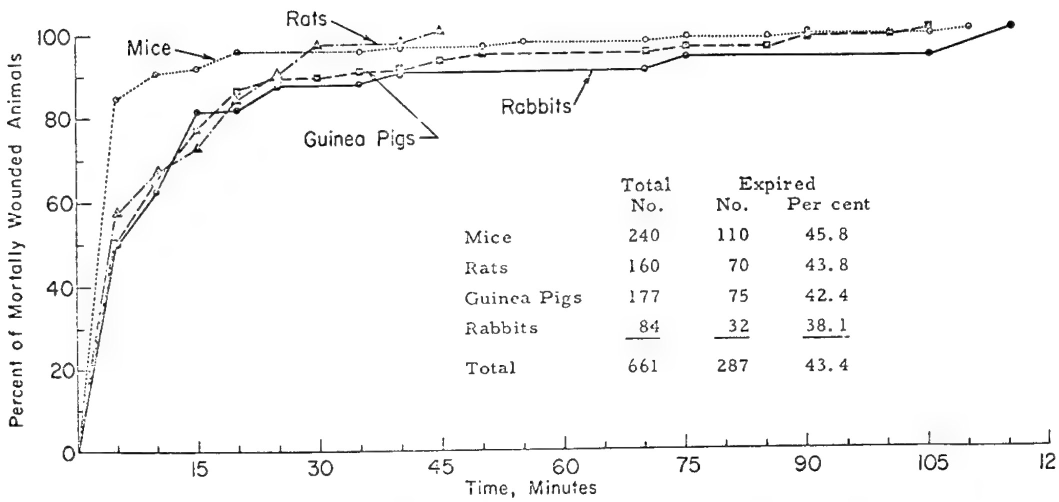
Regarding the tentative criteria for assessing hazards from blast phenomena in air, it can be said that those proposed serve generally for exposures in the open or for a variety of other geometries including structures that might or might not have been initially designed as shelters; viz., criteria for hazards from primary (pressure) effects, from secondary (missile) effects, from tertiary (displacement) effects, and from miscellaneous effects (dust and debris, non-line-of-site thermal radiation, blast-induced fires, etc.). That the criteria are also incomplete as well as tentative is again emphasized here, and it is obvious that extention and refinements are desirable in the future. This statement deserves emphasis in at least three areas.

First, to assess better the influence of the geometry of exposure and to help improve the design of "open" protective structures — if this is really desirable — it is clear that more work needs be done with atypical wave forms.

Second, and related to the above, is the need for learning the effects of oscillating overpressures, mentioned previously, but not emphasized in that portion of the text dealing with criteria. What few data are at hand (see reference 4 for a brief review) are not at all adequate for formulating even crude criteria.

Third, thermal criteria are needed for conditions involving the delivery of heat to the skin, mostly by convective processes, but supplemented by and integrated with radiative and contactual processes.

Fourth, sooner or later, the challenging and complex task of developing data from which criteria for combined injury will evolve will be undertaken. This is of considerable importance in those areas where high and early lethality are involved. For example, Figures 105 and 106 —



	Total No.	Expired No.	Per cent
Mice	240	110	45.8
Rats	160	70	43.8
Guinea Pigs	177	75	42.4
Rabbits	84	32	38.1
Total	661	287	43.4

Figure 105 — *Cumulative percent of mortally wounded animals dying over a two hour period from exposure to "sharp"-rising overpressures of 3 to 4 msec duration* (Ref. 37)

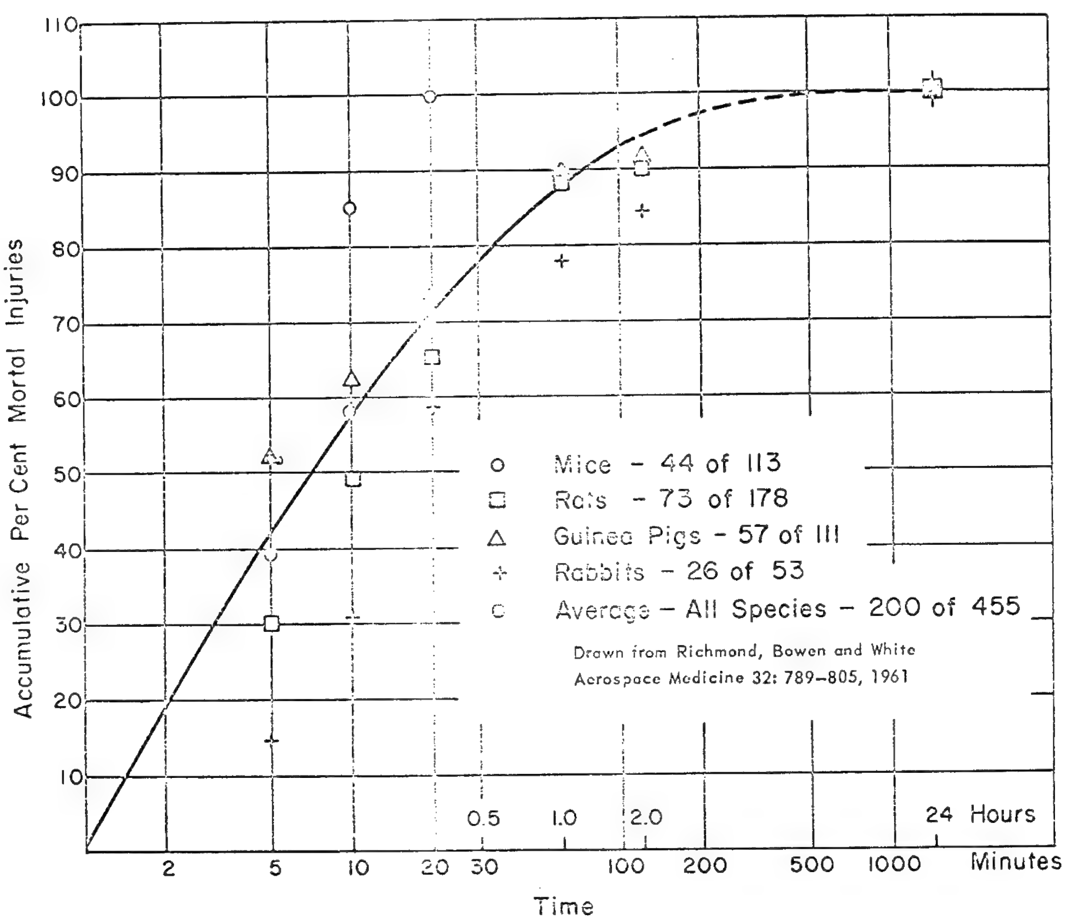


Figure 106 — *Average lethality vs. time observed during* V_{50} *studies.* (Ref. 2, 57)

showing lethality-time curves for the same 4 species of animals subjected to "sharp"-rising overpressures and impact with a hard surface, respectively — will serve to emphasize that rapidly developing lethality is characteristic of serious primary blast injuries as well as those due to whole-body impact. These kinds of data are very significant for at least three reasons; namely, (a) because of the high hazard related with each type of injury, the need to know the effect if both are imposed on an animal or man at nearly the same time can hardly be overemphasized, (b) any therapy likely to be effective must obviously not only be appropriate in kind, but in time, and (c) considerable effort to avoid one or the other, or both, types of injury is clearly justified.

This last point suggests a fifth matter worthy of consideration which stems from the tentative and incomplete nature of the available criteria and the unavailability of those for combined injury. This is the advisability of "designing away" from all recognized hazards in formulating plans for protective construction. For example, many pressure problems — including the need for criteria for disturbed wave forms — "disappear" if a shelter is "closed" and protected with an adequate blast valve. Also dust becomes no worry in shelters if particle sizes are kept large or if the inner surface of a structure is made of material that will not spall.

The main point intended here is simple; namely, since there are inadequacies and gaps in the criteria for assessing hazards and it will take considerable time to remedy such deficiencies, then protective structures should be designed and engineered to avoid all possible areas of uncertainty. This type of thing has been done for ballistic missiles at considerable cost and it certainly can also be done for man.

C. Supporting Data

Finally, the supporting data summarized above to help one better appreciate the validity — or lack of it — embodied in the tentative biological criteria set forth to help elucidate the "state of the art" and the kinds of research needed to refine and extend several of the technologies that can contribute to environmental medicine and the prevention of injury through adequately conceived and designed protective

structures, might well have been more complete and detailed. However, those stimulated to think more thoroughly and deeply about blast-related problems are advised to consult the references in the bibliography. It is hoped that many will do so, for a truly adequate protective structure today must be effective against all and not just one or some of the environmental variations that are hazardous to man.

VI. SUMMARY

A. The nature of the blast-induced hazards related to protective construction was illustrated by summarizing experience with animals exposed in above and below ground structures subjected to nuclear blast during the field operations carried out at the Nevada Test Site in 1953, 1955 and 1957.

B. Environmental variations of consequence that occurred in shelters tested "open" as well as "closed" were:

1. Variations in pressure.

2. High-velocity winds, aided sometimes by ground shock and gravity, that energized penetrating and nonpenetrating missiles and debris arising from inside, outside and the entryways into the structures.

3. Whole-body displacement as a consequence of high-velocity winds, ground shock and gravity and the damage related thereto.

4. Non-line-of-site thermal phenomena due to hot, dust-laden gases and debris, sufficiently severe in some instances to produce carbonizing third degree burns in pigs and complete loss of hair and severe skin burns in dogs.

5. Macroscopic particulates and respirable dust even in "closed" shelters arising from the walls and ceilings as a consequence of ground shock-induced spalling and in some instances probably from air blowing through the ventilation systems protected by sand traps (or other "leaky" devices).

C. Except for the loss of one dog from violent impact subsequent to wind-induced translation and 17 of 20 mice probably from transient

spikes of high reflected pressure, blast survival of "large" and "small" animals located inside "open" below ground shelters was demonstrated at free-field overpressures of over 90 psi (ground range of 1050 ft from a 29-kt explosion on a 500-ft tower). Blast survival was also demonstrated with mice exposed in "closed" structures located at 175 psi (804 ft ground range from a 44-kt explosion on a 700-ft tower).

D. For "open" shelters of certain configurations, the blast related environmental variations inside proved to be greater than those outside the shelter. For other configurations the opposite was true. Thus, the geometric conditions of exposure may either <u>enhance</u> or <u>attenuate</u> hazards from blast phenomena.

E. Tentative biological criteria for estimating human tolerance to blast-induced environmental variations were presented in tabular form as follows:

1. <u>"Fast"-Rising Overpressures of "Long" Duration</u>

<u>Eardrum failure</u>	
Threshold	5 psi (2.3 psi)*
50 per cent	15 - 20 psi (6.2 - 8.0)
<u>Lung damage</u>	
Threshold	10 - 12 psi (4.4 - 5.1)
<u>Lethality</u>	
Threshold	30 - 42 (11 - 15)
50 per cent	42 - 57 (15 - 18)
Near 100 per cent	57 - 80 (19 - 24)

2. <u>Atypical or Disturbed Wave Forms of "Long" Duration</u>

   Tolerance was estimated to increase by about a factor of two for pressures rising to a maximum in two "fast" steps and by a factor of 3 to 5 for wave forms rising smoothly to a maximum in 30 or more msec.

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*The figures in parentheses represent overpressures that on normal reflection will give the maximal value of pressure noted.

3. Nonpenetrating Missiles (10-lb Object)

Cerebral concussion

Mostly "safe"	10 ft/sec impact velocity
Threshold	15 ft/sec impact velocity

Skull fracture

Mostly "safe"	10 ft/sec impact velocity
Threshold	15 ft/sec impact velocity
Near 100 per cent	23 ft/sec impact velocity

4. Penetrating Missiles (10-gm Glass Fragments)

Skin lacerations

Threshold	50 ft/sec impact velocity

Serious wounds

Threshold	100 ft/sec impact velocity
50 per cent	180 ft/sec impact velocity
Near 100 per cent	300 ft/sec impact velocity

5. Impact, Standing Stiff-Legged

Mostly "safe"

No significant effect	< 8 (?) ft/sec
Severe discomfort	8 - 10 ft/sec

Injury

Threshold	10 - 12 ft/sec
Fracture threshold	13 - 16 ft/sec

6. Impact, Seated

Mostly "safe"

No effect	<8 (?) ft/sec
Severe discomfort	8 - 14 ft/sec

Injury

Threshold	15 - 26 ft/sec

7. Skull Fracture from Head Impact

Mostly "safe"	10 ft/sec
Threshold	13 ft/sec
50 per cent	18 ft/sec
Near 100 per cent	23 ft/sec

8. Total Body Impact

Mostly "safe"	10 ft/sec
Lethality threshold	20 ft/sec
Lethality 50 per cent	26 ft/sec
Lethality near 100 per cent	30 ft/sec

9. Non-Line-of-Site Thermal Burns

The lack of criteria for non-line-of-site thermal burns caused by hot, dust-laden air moving at high velocities was noted, but data from Ashe and Roberts[67] were cited to show temperature-time conditions for transient redness of the skin, and for first and second degree burns in human volunteers when air at various temperatures was blown at 6 liters per minute through a tube 1 cm in diameter onto the subject's skin.

10. Dust Asphyxia

No attempt was made to formulate criteria for particulates of low, intermediate or high toxicity due to radioactivity or otherwise. However a calculation, following Desaga,[24] was made of the time it might take in adults to produce dust asphyxia for "normal" and maximal ventilation of 10 and 90 liters per minute, respectively, at various assumed dust concentrations.

F. Supporting data from the literature and ongoing programs in environmental medicine from which the tentative biological blast criteria were drawn were cited not only to help the reader assess the validity of

the criteria, but to elucidate the use of extrapolations from animal data, to point out the employment of "best estimates" where data were inadequate or absent, and to note wherein "state of the art" concepts bear upon attempts to estimate human blast tolerance at the present time.

G. The implications of the full-scale, field experience with shelters, tentative criteria for assessing blast hazards and selected data supporting the latter were briefly discussed. Among other things emphasized was the fact that while "open" structures had without question enhanced survival, they also proved extremely hazardous on a variety of occasions. As a consequence, and even though no "open" structures carefully designed to serve as a shelter had been tested, proof of adequacy as means of protection was considered a responsibility of those who might favor "open" rather than "closed" designs.

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